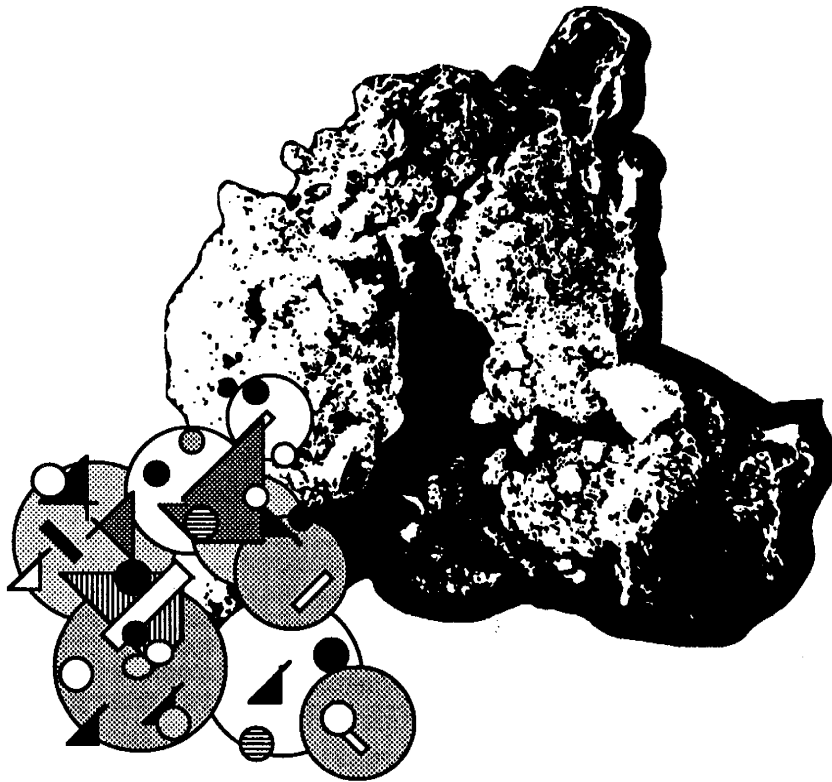


WORKSHOP ON PRODUCTION AND USES OF SIMULATED LUNAR MATERIALS



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WORKSHOP ON

*Production and Uses
of
Simulated Lunar Materials*

Convened by

David S. McKay
James D. Blacic

Sponsored by
NASA Johnson Space Center

Hosted by
Lunar and Planetary Institute
Houston, Texas
September 25-27, 1989

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i. Foreword

On September 25-27, 1989, a workshop entitled "Production and Uses of Simulated Lunar Materials" was convened at the Lunar and Planetary Institute in Houston, Texas, to define the need for simulated lunar materials and examine related issues in support of extended space exploration and development. Lunar samples are a national treasure and cannot be sacrificed in sufficient quantity to test lunar resource utilization processes adequately. Hence, the workshop focused on a detailed examination of the variety of potential simulants and the methods for their production. The workshop participants also touched on policy issues concerned with making and distributing simulants. Policy recommendations presented in this report are the consensus of the convenors and session leaders. Substantial contributions were made to the writing of this report by P. W. Weiblen, L. A. Taylor, and J. H. Allton. The workshop participants hope this report will be useful as a guide to potential producers and users of simulated lunar materials, and to NASA in developing policy related to research on extraterrestrial resource utilization.

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NASA PHOTO NO. AS-12-46-6780

I. EXECUTIVE SUMMARY

Introduction

The establishment of a lunar base will provide access to a large resource of planetary materials that will facilitate the evolutionary extension of human presence into space. To achieve this, the technology of lunar *in situ* resource utilization must be developed. It is not appropriate to expend valuable lunar samples in this effort. Therefore, terrestrial simulants must be produced for distribution to the research community. Simulants of lunar rocks and soils with appropriate properties, although difficult to produce in some cases, will be essential to meeting the system requirements for lunar exploration.

Characteristics of Lunar Materials Matched to Potential Terrestrial Simulants

Lunar rocks and soils present a unique set of physical and chemical properties. In contrast to terrestrial rocks, the highlands and mare rocks do not contain minerals with ferric-iron or hydrous phases. The lunar soils are likewise unique. Spheres, angular shards, and the vesicular, fragile, impact-glass-welded aggregate grains called agglutinates are among the diverse particles found in lunar soils. The fine-grained lunar soils are cohesive with high *in situ* bulk densities of nearly 2 g/cm³. It is important to note that they do not contain clays and other weathering products so characteristic of terrestrial soils. An additional and important property of lunar soils has been imparted by the solar wind, which has implanted small amounts of hydrogen, helium, and other volatiles in the outer surfaces of soil grains.

Properties of lunar materials important to simulate include size distribution, electrostatic and magnetic properties, geomechanical properties (strength, density, etc.), and the special properties of friability of agglutinates with single-domain iron, chemical reactivity, bulk chemical composition, modal composition, texture, and the presence of implanted solar-wind gases.

Potential terrestrial rock feedstocks for simulants have been identified for high-Ti mare basalts, low-Ti mare basalts, KREEP basalts, ferroan anorthosites, and high-Mg anorthosites. Certain special properties can be approximated with individually created simulants (e.g., ilmenite with no Fe³⁺) or from meteorites.

Simulant Production Processes and Recommended Initial Suite of Simulants

Basic production processes include crushing and sieving rocks and synthetic glasses, concentrating minerals from natural and synthetic sources, and generation of glass spheres and agglutinates. Ion-implantation and impact shock damage can be done on a small scale.

Techniques for making glass and glass/lithic components specifically to simulate lunar characteristics including agglutinates are being developed at the University of Minnesota.

Activities at a lunar base that are currently being studied include resource production, mechanical operations, and agriculture and health studies. Simulants must be found for different processes and methods related to these activities. A matrix is presented that relates these endeavors to the properties, starting materials, production methods, and projected amounts of simulant needed (Table 6) .

Five terrestrial feedstocks have been identified that approximate the bulk chemical and mineralogical properties of the following lunar rocks and soils: high-Ti basalt, low-Ti basalt, KREEP basalt, ferroan anorthosite, and anorthosite. Each of these feedstocks could be crushed and sieved into various size fractions. Homogeneous glasses and agglutinates can also be produced from these rock feedstocks.

By making adequate amounts of these simulants available, they will become standards through which test results can be compared. As standard properties are determined and used, the characterized database grows, making the simulants more valuable.

Characterization, Validation, and Distribution of Simulants

There is an urgent need for the characterization, validation, and distribution of simulants to be linked in a coordinated way to the production of simulants. There is also a need for a dedicated NASA organization to assume responsibility for integrating these activities.

Coordinating these activities should be the responsibility of NASA's Mission Science and Technology Office, and could be accomplished by designating a Simulant Advisory Committee of experts to set policy, and by providing a dedicated staff person to execute this policy as a Simulant Curator.

Recommendations

1. *It is strongly recommended that lunar simulant components be produced and made available to researchers as soon as possible.*
2. *The Mission Science and Technology Office should immediately designate a lunar simulant curator and establish a lunar simulant advisory committee.*
3. *Every effort should be made to assist the research community with appropriate knowledge transfer concerning the feasibility and design of specific experiments requiring simulants.*



NASA PHOTO NO. AS-16-116-18690

II. INTRODUCTION

We are in the midst of a new age of exploration precursory to the settlement of space by humans. The early reconnaissance phase is over, and we are about to embark on new voyages of discovery that will be followed by developers and settlers. At this time, NASA is formulating plans to implement an evolutionary extension of human presence into space. These plans call for the use of extraterrestrial resources. For example, lunar oxygen will be used as rocket propellant to reduce the flight costs and facilitate individual missions. A key step in the strategy for developing space will be the establishment of a manned lunar base. This will open access to the tremendous resources of planetary materials.

For a lunar base, it will be necessary to design and test processes and equipment on Earth to develop practical methods for using lunar resources and dealing with the lunar environment. The lunar sample collection provides an invaluable resource for constraining the research required to assure the success of a viable lunar base in the future. However, because the collection is too valuable and too small to meet the needs of such research, it is necessary to develop simulants for the water-free and meteorite-impact-modified lunar materials. For the lunar environment, the harsh vacuum (10^{-14} Earth atmosphere) and night-to-day thermal cycling (about -158° to $+122^{\circ}\text{C}$ at mid-latitudes) are costly to simulate; the $1/6$ gravity is almost impossible to simulate on Earth for any protracted period. Thus it is clear that the unique materials properties and environmental features of the Moon put serious constraints on the Earth-bound development of practical methods for establishing a lunar base and testing lunar resource processing systems.

The unique set of properties of lunar rocks and soils are inherited from their formation in an anhydrous and reducing environment, subsequent modification by meteorite impact, and billions of years of exposure to solar wind and intense radiation in an ultrahigh vacuum. Many of these properties are difficult to simulate.

Lunar Simulant:

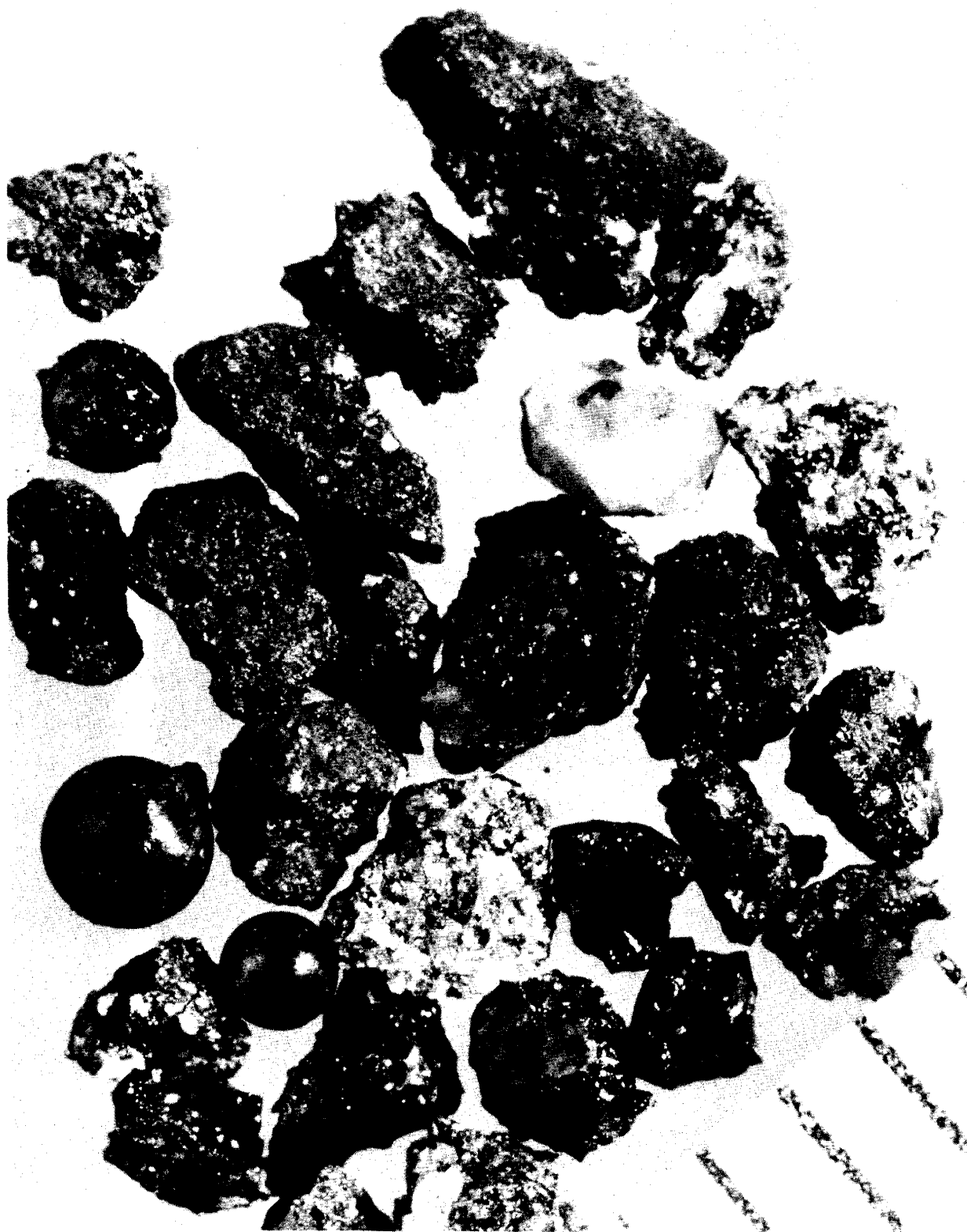
Any material manufactured from natural or synthetic terrestrial or meteoritic components for the purpose of simulating one or more physical and/or chemical properties of a lunar rock or soil.

Fortunately, not all the characteristics of lunar samples need to be duplicated. In fact the cost of a "near-perfect" lunar simulant would be prohibitive. A variety of

simulants should be developed, each exhibiting the particular lunar characteristics essential to a specific experiment. The types of simulated lunar materials needed are governed by the range of endeavors to be pursued at a lunar base. Broadly, these involve:

<i>resource production</i>	(extraction of chemically bound oxygen and metals, recovery of solar-wind implanted gases such as hydrogen and helium, and raw materials for construction)
<i>mechanical operations</i>	(construction, surface transportation, mining, and mineral beneficiation)
<i>biological activities</i>	(maintenance of a closed ecological life support system and lunar agriculture)

The scope of the effort required to provide adequate simulants will be constrained by the variety of lunar resource materials to be exploited. There are basically only two broad categories of lunar geologic materials (i.e., rocks and soils) from two different geologic terrains (i.e., highlands and maria).



NASA PHOTO NO. 70-55663

III. CHARACTERISTICS OF LUNAR MATERIALS MATCHED TO POTENTIAL TERRESTRIAL SIMULANTS

Selection of specific terrestrial rocks for use as lunar simulants is constrained by differences in original bulk composition and the environment and mode of formation of lunar and terrestrial rocks. The three most important differences are the absence of water in lunar materials, the ubiquitous presence of native iron (Fe^0) as a stable phase, and the absence of ferric iron (Fe^{3+}) in iron-bearing minerals. In addition, lunar soils reflect the effects of meteorite impact, solar-wind, solar-flare, and galactic cosmic implantation, and radiation. In contrast, terrestrial rocks contain hydrous phases, ferric iron is present, and the effects of meteorite impact are found in only rare and highly selective occurrences.

The selection of a feedstock from terrestrial rocks is facilitated by the exceptional database that exists for lunar materials. The database includes observations from lunar orbit, data collected during the Apollo missions, data from experiments left on the lunar surface, and the extensive results of the studies of the returned samples (over 380 kg from the six Apollo manned missions and three Luna robotic missions). A comprehensive summary and review of this database, along with the results of new analyses and interpretations, are available in the *Lunar Sourcebook* (Heiken et al., 1991). A brief introductory guide to lunar soils can be found in Allton et al. (1985) and Taylor (1987, 1990a). A concise summary of lunar rocks and minerals, as well as a useful bibliography can be found in Taylor (1990b). Extended reviews of the chemistry, mineralogy, and petrology of mare basalts and the lunar regolith are provided by Papike et al. (1976, 1982) and Heiken (1975).

Lunar Rocks

Studies of the lunar samples have established that the earliest planetary highlands crust consisted of at least two distinct suites of plagioclase-rich rocks, ferroan anorthosite and Mg-rich rocks (Warren and Wasson, 1980). These highlands primordial crustal rocks have been fragmented and reconstituted during the long history of meteorite impact on the Moon to form a secondary class of rocks, the highlands breccias. It would be difficult to find terrestrial analogs for these breccias, but fortunately most lunar base scenarios involve a mare site, and, as yet, highlands rocks have not figured heavily in the consideration of lunar materials for resource production. Terrestrial anorthositic rocks can provide analogs for the mineralogy and bulk chemistry of the two suites of highlands rocks.

The infilling of the maria includes over ten different chemical varieties of basalts (Papike et al., 1976). Lunar mare basalts range from completely crystalline

to glassy, and exhibit a wide variety of complex and well-preserved quench textures. Chemical and mineralogical analogs can be found for major mare rock types: high-Ti, low-Ti, and KREEP basalts. However, the quench textures in terrestrial volcanic rocks are not as diverse as in mare basalts, and terrestrial glasses have suffered some degree of devitrification and oxidation.

Lunar Soils

The entire lunar surface is covered completely by a layer of fragmented and unconsolidated rock material called **regolith**. The thickness of this thin veneer of rock debris is typically rather small, ranging from 3-5 m in mare regions to 10-20 m in highland areas. The term **soil**, although sometimes used synonymously with regolith, actually refers to the finer fraction (<1 cm) of the unconsolidated material of the regolith. The bulk of the lunar soil (approximately 80-90 wt%) is less than 1 mm. The lunar soil was formed by three basic processes: (1) simple **comminution**--disaggregation of rocks and minerals into smaller particles by micrometeorites (which are also incorporated into the soil); (2) **agglutination**--the welding of lithic and mineral fragments together by the glass resulting from micrometeorite-produced impact melt; and (3) solar-wind **spallation and implantation**--although only producing minor amounts of weathering, the solar-wind additions are highly significant, as discussed below (Taylor, 1990a). The first two processes compete to decrease and increase, respectively, the grain size of soil particles. The glass-welded **agglutinates** are a unique component of the lunar soils with no terrestrial analog.

Mixing by large-scale impacts introduced some highlands material into mare soils and vice versa, but extensive lateral mixing due to small-scale impacts is restricted to a few kilometers (Papike *et al.*, 1982). Overall, the local lithologic diversity dominates the character of the lunar soils at the different sites sampled thus far on the Moon (Fig. 1). The highlands soils, developed on anorthositic bedrock, are relatively enriched in aluminum and calcium, while mare soils, developed on basaltic bedrock, are relatively enriched in iron, magnesium, and titanium (Table 1).

The disaggregation of rocks by the impact process has produced soils that can be described in familiar terrestrial terms as well-graded silty sands or sandy silts with an average particle size (by weight) between 0.040 and 0.130 mm for the submillimeter fraction (Carrier *et al.*, 1973) (Fig. 2). The density of *in situ* bulk lunar soil, as determined from large-diameter core tube samples, is typically 1.4 to 1.9 g/cm³ (Allton *et al.*, 1985). The bulk density increases with depth, and below 10-20 cm the soil is often at higher density than is required to support the overburden in lunar gravity (Carrier *et al.*, 1973). Spheres, angular shards, and fragile, reentrant, vesicular grains are among the diverse shapes found in most lunar soils. The most abundant particles composing the soil are rock, mineral,

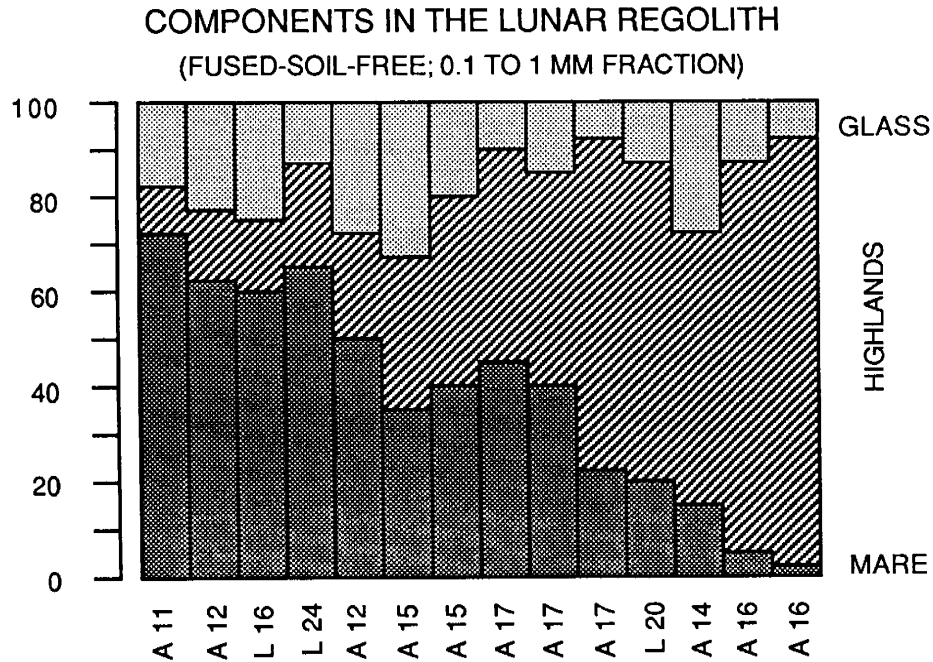


Fig. 1. Components of lunar regolith (modified from *Papike et al.*, 1982). Relative proportions of fragments of mare rocks, highlands rocks, and glass in the 0.1-to 1-mm fraction of the lunar regolith are shown for Apollo (A) and Luna (L) sites. Apollo 11 and 12 and Luna 16 and 24 sites are dominated by mare materials, Apollo 16 by highlands materials, and other sites vary depending on their proximity to mare/highlands boundaries.

TABLE 1. Major element compositions (values given in wt%) of soils from the Apollo landing sites (1982).

Apollo sample	11 10084	12 12001	12 12033	14 14163	15 15221	15 15271	16 64501	16 67461	17 70009
SiO ₂	41.3	46.0	46.9	47.3	46.0	46.0	45.3	45.0	40.4
TiO ₂	7.5	2.8	2.3	1.6	1.1	1.5	0.37	0.29	8.3
Al ₂ O ₃	13.7	12.5	14.2	17.8	18.0	16.4	27.7	29.2	12.1
FeO	15.8	17.2	15.4	10.5	11.3	12.8	4.2	4.2	17.1
MgO	8.0	10.4	9.2	9.6	10.7	10.8	4.9	3.9	10.7
CaO	12.5	10.9	11.1	11.4	12.3	11.7	17.2	17.6	10.8
Na ₂ O	0.41	0.48	0.67	0.70	0.43	0.49	0.44	0.43	0.39
K ₂ O	0.14	0.26	0.41	0.55	0.16	0.22	0.10	0.06	0.09
MnO	0.21	0.22	0.20	0.14	0.15	0.16	0.06	0.06	0.22
Cr ₂ O ₃	0.29	0.41	0.39	0.20	0.33	0.35	0.09	0.08	0.41
Σ	99.8	101.0	100.8	99.8	100.5	100.4	100.3	100.8	100.5

Sources: *Laul and Papike* (1980) PLC , 11, 1307; *Laul et al.* (1978) PLC , 9, 2065.

and glass fragments (Fig. 3), plus the unique lunar agglutinates (Fig. 4). The latter are aggregates of the various soil components welded together with impact-produced glass. The glass component of the agglutinates contains myriad single-domain native iron grains (40-200 Å). This native iron is a product of reduction by solar-wind-implanted hydrogen during the impact melting. Data on the variation in proportions of the soil components with grain size are listed in Table 2.

The Moon's lack of a global magnetic field has allowed solar wind and solar and galactic cosmic rays to cause minute structural damage to the grains and to implant certain particles as well. These effects are more concentrated in smaller grains and, of course, are dependent upon the length of time the grains were exposed on the surface. The solar-wind particles consist of protons (hydrogen nuclei) and alpha particles (helium nuclei), with lesser amounts of many other elements (e.g., carbon, nitrogen). These are implanted in the outer few hundred angstroms of lunar soil grains in significant abundances (e.g., 50-100 ppm hydrogen and nitrogen, with somewhat more carbon) and are easily recovered from the soil by simple roasting (Taylor, 1990a).

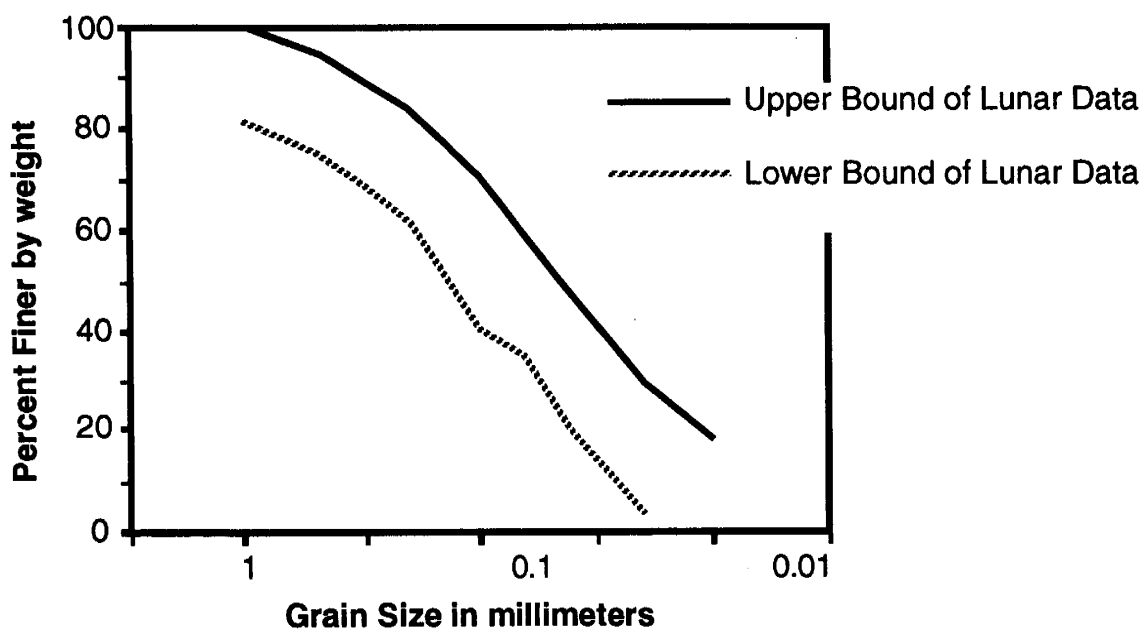


Fig. 2. Grain size distributions of lunar soil (modified from Carrier *et al.*, 1973).

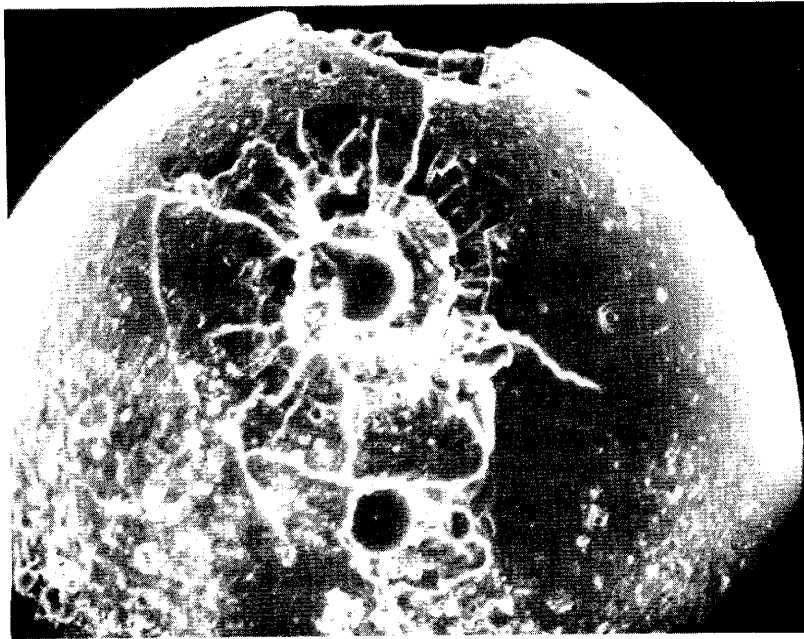


Fig. 3. One-millimeter-diameter lunar glass sphere with micrometeorite impact pit (photo courtesy D. S. McKay, NASA photo S71-48106).



Fig. 4. One-millimeter-diameter agglutinate (photo courtesy D. S. McKay, NASA photo S71-24575).

TABLE 2. Petrography of a series of size fractions from 71061, a typical Apollo 17 mare soil (modified from *Heiken, 1975*).

COMPONENTS	<20 μ m	20-45 μ m	45-75 μ m	75-90 μ m	90-150 μ m	150-250 μ m	250-500 μ m
Agglutinates	17.0	17.3	13.0	17.3	9.3	11.8	10.0
Basalt			9.6	16.6	19.6	34.3	51.5
Breccia			2.3	6.6	5.8	7.9	8.4
Anorthosite					0.3		
Cataclastic anorthosite			1.0				
Norite							
Gabbro							0.5
Plagioclase			16.3	7.0	17.3	9.0	8.5
Clinopyroxene			21.3	26.3	21.0	17.4	10.8
Orthopyroxene							
Olivine						0.6	
Ilmenite			6.0	3.3	4.6	3.3	2.3
Glass			28.3	22.4	21.8	14.6	8.4
Other			2.0			1.0	
Total grains counted	300	161	300	300	300	178	130
Wt% of each size fraction	17.98	12.21	8.39	3.0	8.66	7.04	7.08

Except for the last line, all data are in volume percent.

Properties to be Simulated

A list of properties of lunar materials relevant to lunar base research from diverse perspectives appears in Table 3. Unforeseen applications or innovative processes could well require simulation of additional properties.

TABLE 3. Properties to be simulated.

- | | |
|-----|---|
| 1. | Grain properties |
| | a) Size distribution |
| | b) Size/shape distribution |
| 2. | Electrostatic charging properties |
| 3. | Magnetic properties |
| 4. | Geomechanical properties |
| | <u>Mechanical</u> |
| | a) Fatigue |
| | b) Strength |
| | i. Tensile |
| | ii. Compressive |
| | iii. Shear |
| | iv. Grain hardness |
| | v. Coefficient of friction |
| | c) Flexural strength - bending resistance |
| | d) Fracture properties |
| | e) Impact resistance |
| | f) Rheology (aggregate flow properties) |
| | g) Angle of repose |
| | <u>Physical</u> |
| | h) Thermal properties |
| | i) Bulk density |
| | j) Particle density |
| | k) Porosity |
| | l) Surface area |
| | m) Permeability (gas) |
| 5. | Agglutinate-specific |
| | a) Friability |
| | b) With single-domain iron |
| 6. | Chemical reactivity |
| | a) From surface damage |
| | b) As volatile/soluble minerals |
| 7. | Chemical properties |
| | a) Bulk |
| | b) Mineral |
| | c) Glass |
| 8. | Modal composition |
| | a) Total |
| | b) As a function of grain size |
| 9. | Texture |
| 10. | Implanted solar particle-specific (e.g., H, C, N) |

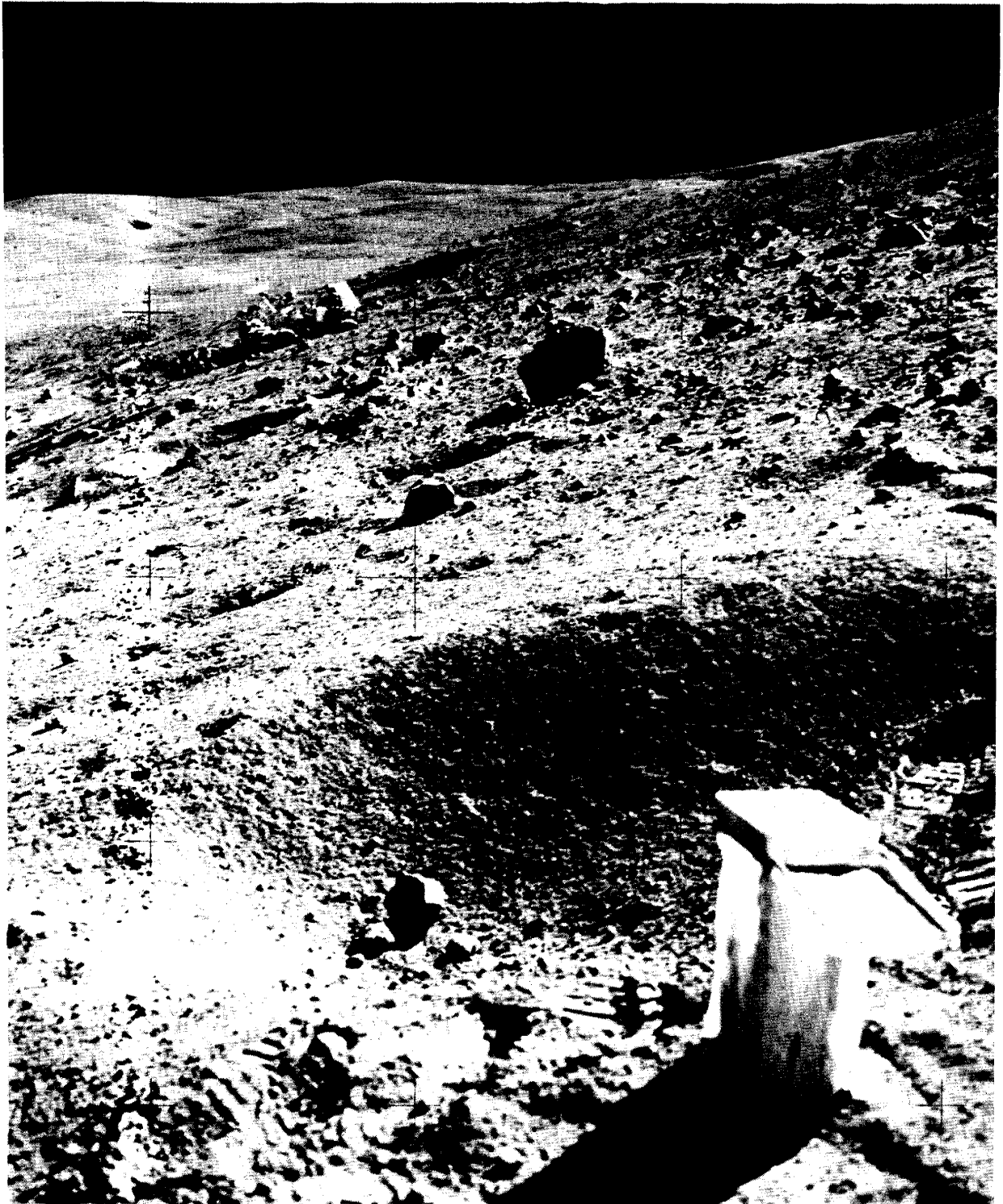
Potential Terrestrial Feedstocks for Producing Simulated Lunar Materials

The best feedstocks will be those that match, as closely as possible, the bulk chemistry, mineralogy, and texture of a specific lunar material. Candidate terrestrial simulant feedstocks for the major lunar rock types are listed in Table 4, along with special materials needed to duplicate unusual properties. Since the components of the lunar soils are derived from these rock types, they will also serve as feedstocks for the production of simulants for lunar soils. The special properties of ion-implanted grains, ilmenite without ferric iron, and glasses with single-domain iron in the lunar soils might be approximated with meteorites and/or individually fabricated materials.

TABLE 4. Potential terrestrial feedstocks for simulated lunar materials.

LUNAR MATERIAL	POTENTIAL TERRESTRIAL FEEDSTOCK
1. High-Ti mare basalt	High-Ti Keweenawan basalt from Duluth, MN
2. Low-Ti mare basalt	Wide variety of Keweenawan basalts, Triassic basalts from eastern U.S., Hawaiian basalts
3. KREEP* basalts	Keweenawan basalt
4. Ferroan anorthosite	Anorthosites from Stillwater complex, MT
5. High-Mg anorthosite	Noritic anorthosite from Stillwater complex, MT
6. Special materials	a. Meteorites b. Synthetics (e.g., ilmenite without ferric iron) c. Ion-implanted materials d. Bulk glasses

*Potassium, rare-earth element, and phosphorous-enriched basalt.



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IV. SIMULANT PRODUCTION PROCESSES AND RECOMMENDED INITIAL SUITE OF SIMULANTS

Basic Production Processes

The extent and nature of the processing of the simulant feedstocks will depend on the specific use for which a given simulant is needed. Processing should be carried out with documented, reproducible methods. The basic production processes listed in Table 5 will provide either final products, ready for use, or intermediate components that can be combined for specific uses.

TABLE 5. Basic production processes.

1. Select and collect appropriate terrestrial rocks.
2. Crush and sieve rocks to different particle sizes.
3. Separate and concentrate specific minerals from <ul style="list-style-type: none"> a. natural sources b. synthetic sources
4. Produce glass.
5. Produce agglutinates with and without native iron, including single-domain iron metal.
6. Produce other special properties, for example <ul style="list-style-type: none"> a. implanted ions b. shock-damaged grains

The processes listed in Table 5, some of which need further development, can be used to produce the following categories of components from which most simulants can be made. Many uses will require custom blending or further treatment of these components.

1. Rock fragments. Crushing and grinding of different terrestrial rocks with subsequent sieving and remixing of appropriate size distributions could be used to approximate the particle size distributions of rock fragments found in mare and highland soils.

2. Mineral fragments. Many mineral fragments obtained from terrestrial sources will contain ferric iron and may have associated hydrous phases. For some minerals, like anorthite, terrestrial sources may suffice. However, for others such as ilmenite it may be necessary to synthesize ilmenite without Fe^{3+} or to use a meteoritic source.

3. **Glasses.** Natural glasses may suffice for many process experiments. However, in those cases where anhydrous glass is required, rocks of appropriate composition could be fused under anhydrous conditions.

4. **Glass spheres.** Micrometeorite impacts and pyroclastic volcanism have produced many small glass spheres in the lunar regolith. Fabrication of similar spheres is being developed in an in-flight, sustained, shockwave plasma reactor (Appendix B).

5. **Agglutinates.** Agglutinates are small (generally less than a millimeter or two) aggregations of lithic and mineral fragments welded together by silicate glass. It may be possible to replicate their gross features with various schemes, but one of their key properties--the myriad single-domain native iron grains (40-200 Å)--may be difficult to reproduce.

6. **Material with shock-deformation effects.** Meteorite impacts have produced deformational effects ranging from coarse-scale shattering to glass formation without melting in lunar materials (e.g., maskelynite). The full range of shock effects may be difficult to replicate in quantity.

7. **Material with implanted ions.** The production of simulated soil grains with implanted ions (*cf.*, solar-wind particles), to test gas extraction methods, will not be easy.

Production Methods

The basic production processes for crushed and sized rock and mineral fragments (Table 5) are well-developed ore/mineral processing procedures that could be used with little or no modification. Concern for contamination must be commensurate with the use of the simulant.

A plasma melting technique for the production of glass and glass/lithic components (*cf.*, agglutinates) on a relatively large scale is under development at the University of Minnesota (Weiblen *et al.*, 1990). This process generates mixtures of glass and rock fragments starting from crushed rock feedstocks. In some cases the textures created are similar to those found in lunar soil. A brief description of the method is given in Appendix B.

Characteristics of Simulants for Specific Uses

Table 6 is a matrix of lunar base endeavors and the data on simulants contained in Tables 3-5. It supplies the critical properties to simulate (ranked in

order of priority), the starting materials from which to make the simulant, production methods, and the estimated demand. The matrix is not intended to be exhaustive, but covers many of the most frequently referenced activities projected for a lunar base. The numerical references for critical properties are keyed to Table 3, starting materials to Table 4, and production methods to Table 5.

TABLE 6. Potential lunar simulants and their applications.

(a) Resource Production.

USE OF SIMULANT	PROPERTIES from Table 3	STARTING MATERIALS from Table 4	PRODUCTION METHODS from Table 5	DEMAND (grams)		NOTES
				Bench scale	Pilot scale	
OXYGEN						
A. Ilmenite reduction						
1. Beneficiation studies						
a. Soil simulant	$8b > 1 > 7b = 5b > 3 = 2$	1	1,2,4,5	10^3	10^5	
b. Rock simulant	$8a = 4b = 4d = 7b > 3 > 9$	1	1	10^3	10^5	Not possible to include ilmenite without Fe^{3+} .
2. Production studies	$8a = 1 = 7b > 6a$	6b	3b	10	10	The simulant should include appropriate amounts of trace contaminants such as sulfur, likely to be found in real lunar feedstock.
B. Magma electrolysis, including fluoride flux	7a	1-5	1	10^3	10^5	
C. Bulk soil pyrolysis	7a	1-5	1	10^3	10^5	
SURFACE GAS EXTRACTION						
Bulk soil pyrolysis	$10 > 7 > 1 = 4$	1-5	1-3,4,6a	10	10^3	Synthetic or natural materials must be as anhydrous as possible.

USE OF SIMULANT	PROPERTIES from Table 3	STARTING MATERIALS from Table 4	PRODUCTION METHODS from Table 5	DEMAND (grams)		NOTES
				Bench scale	Pilot scale	
METALS PRODUCTION						
A. Iron						
1. Carbonyl process, bulk soil	8b>1a>7b=5b	1-5a,d	1-3	10	10 ⁴	Simulant can contain native Fe or Fe from the byproduct of the ilmenite reduction O ₂ production process.
2. Magma electrolysis, bulk soil	7a>>1	1-5a,d	1	10 ⁴	10 ⁵	Trace contaminants such as S may be important.
B. Silicon						
1. Fluoride electrolysis, bulk soil	7a>>1	4	3	10 ⁴	10 ⁵	
2. Magma electrolysis, bulk soil	7a>>1	1-5a,d	1	10 ⁴	10 ⁵	Trace contaminants such as S may be important.
C. Aluminum						
same as for silicon						
D. Calcium						
1. Fluoride electrolysis, bulk soil	7a>>1	4	1,3a	10 ⁴	10 ⁵	
2. Magma electrolysis, bulk soil	7a>>1	1,4	1	10 ⁴	10 ⁵	

(b) Mechanical Operations

USE OF SIMULANT	PROPERTIES from Table 3	STARTING MATERIALS from Table 4	PRODUCTION METHODS from Table 5	DEMAND (grams)		NOTES
				Bench scale	Pilot scale	
CONSTRUCTION						
A. Sintering of bulk soil	7a-c>1a>4h-l>2>6a	1-6	1,2,4,6	10 ³	10 ⁵	Defect content is particularly important for microwave sintering. Hydrous mineral content should be minimized and documented in all cases.
B. Melting of bulk soil	7a-c>1a>8>4h-l>2>6b	1-6	1,2,6	10 ³	10 ⁵	Take same precautions as sintering.
C. Explosive excavation of regolith	1a,b=4b,i,g	1-5	1,2	10 ⁴	10 ⁶	Particle size sorting and compaction of the soil should attempt to duplicate lunar soil mechanical properties (e.g., cohesion, angle of repose).
D. Mechanical excavation of regolith	1a,b=2=4b>4i,g	1-5	1,2	10 ⁴	10 ⁶	Particle size sorting and compaction of the soil should attempt to duplicate lunar soil mechanical properties (e.g., cohesion, angle of repose).
EQUIPMENT TESTING						
A. Regolith moving and handling	4b,d,g,i,f=1>2>3	2,1	1	10 ⁴	10 ⁶	Particle size sorting and compaction of the soil should attempt to duplicate lunar soil mechanical properties (e.g., cohesion, angle of repose). In large-size simulations, boulder-sized particles should be included.

USE OF SIMULANT	PROPERTIES from Table 3	STARTING MATERIALS from Table 4	PRODUCTION METHODS from Table 5	DEMAND (grams)		NOTES
B. Trafficability	4a,b,i,k=1	2,1	1	Bench scale	Pilot scale	Particle size sorting and compaction of the soil should attempt to duplicate lunar soil mechanical properties (e.g., cohesion, angle of repose). In large-size simulations, boulder-sized particles should be included.
				10 ⁴	10 ⁷⁻⁹	
C. Dust control	1=2>6a=5a	1-5	1-3,4	10 ³	10 ⁴	
D. Tribology (friction, wear, abrasion)	4b,i,k=1>2=6	1-5	1-4,6a	10 ²	10 ⁴	Grain hardness and friction properties are very important. Consideration should be given to reactivity with seal materials.

(c) *Biological Activities*

USE OF SIMULANT	PROPERTIES from Table 3	STARTING MATERIALS from Table 4	PRODUCTION METHODS from Table 5	DEMAND (grams)		NOTES
Soil-based agriculture	1=7a-C=6=1=8b=6a, 6b=4	1-6	1,2,4,5,6a	Bench scale	Pilot scale	It will be difficult to exclude the oxidized metals (Fe ³⁺ , Mn ^{3 to 5+} , etc.) and hydrous minerals found in terrestrial sources that would not be present in a lunar soil.
				10 ³	10 ⁵	
Toxicity, aerosol studies	1b=7=6=2=5a	1-6	1,2,4,5,6a	10 ³	10 ⁵	

Suite of Simulants for Initial Production

It can be seen by examination of the potential simulants listed in Table 6 that many of them have common properties. Hence, it is clear that production of simulant components that can be combined in various ways for specific uses would be the most efficient way to meet the requirements of different users. As an example of this concept, the five terrestrial rocks listed in Table 4 could provide bins of feedstocks for three distinct sets of simulants:

Set I: Each of the five feedstock rocks could be crushed and sized. Typical size fractions might be $<44\ \mu\text{m}$, $44\text{-}150\ \mu\text{m}$, and $150\text{-}1000\ \mu\text{m}$. This will result in 20 bins of simulant components: 5 bins of initial rock stock, 5 bins of grain split #1, 5 bins of grain split #2, and 5 bins of grain split #3.

Set II: One basalt feedstock and one anorthosite feedstock could be made into homogeneous glass and then crushed and sized. Alternative feedstocks are bulk glasses produced commercially to match chemical compositions of basalt and anorthosite. This will result in eight bins of simulant components: two bins of raw glass stock, two bins of grain split #1, two bins of grain split #2, and two bins of grain split #3.

Set III: The same basalt and anorthosite feedstocks in Set I used to make glass in Set II could be used for partial melt processing to produce an agglutinate-like texture of mixed rock and glass fragments. This will result in at least one bin of the simulant components.

Sufficient quantities of these 29 bins of simulant components should be produced to provide for several years' anticipated testing, and this material should be made available to those conducting the tests. In this way the simulant components become standards through which test results can be compared. As these standard components are characterized and used, the database of component properties grows, making the components all the more valuable.

Another benefit of having these well-characterized components available is flexibility in creating custom simulants for each use. Researchers can select any of the 29 components to further process (e.g., implant hydrogen in glass of grain split #1) and to blend with any of the other components in varying proportions.



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V. CHARACTERIZATION, VALIDATION, AND DISTRIBUTION OF SIMULANTS

One reason for convening the workshop was the Lunar and Planetary Sample Team's (LAPST) requirement for experimenters to prove their techniques on appropriate, well-characterized simulants before being allocated lunar samples. Ways of providing and validating that a simulant is appropriate need to be devised. Although nothing precludes individuals from making and using their own simulants, there is much to be gained from working with documented simulants. There is also a need for defining standards for simulant properties and for specifying the characterization testing procedures to be used. Equitable and efficient methods for distribution are required.

There is an urgent need for the validation and distribution of simulants to be linked in a coordinated way to the production of simulants and for a dedicated NASA organization to assume responsibility for integrating these activities.

Coordinating activities of academic, commercial, and government organizations all focused on the goal of providing or using appropriate, well-characterized simulants should be the responsibility of NASA's Mission Science and Technology Office. This Office can best accomplish this task by designating a Simulant Advisory Committee (SAC) to set policy and a dedicated staff person to execute this policy as a Simulant Curator. The relatively centralized organizational plan, shown in Fig. 5, is an example plan that contains many of the elements that need to be considered.

The interactions among simulant users (Principal Investigators), manufacturers, property characterization testing laboratories, the proposed NASA coordinating organization, the committee setting policy and standards for simulants, and the committee charged with the allocation of true lunar material (LAPST) are necessarily complex. Typical details of these interactions could be the following:

1. **The Simulant Advisory Committee (SAC)** is composed of experts in lunar materials (perhaps members of LAPST) and experts in the traditional disciplines that have application to a lunar base. This committee:
 - Provides expertise and sets policy;
 - Serves as a liaison between producers and PIs; recommends simulant sources;
 - Defines standards for simulant properties and identifies approved labs for characterizing these properties;

- Reviews procedures written by Approved Characterization Labs for measuring properties of simulants; and
- Makes recommendations to LAPST on simulant quality and appropriateness.

2. Principal Investigators:

- Procure or manufacture simulants;
- Request analysis by Approved Characterization Labs via the Simulant Curator; and
- Provide Simulant Curator with representative sample and any available characterization data for registered simulants.

3. Simulant Curator (part of NASA's Mission Science and Technology Office):

- With a permanent location and dedicated staff, serves as an administrative agent for the SAC and a single point of contact for PIs;
- Archives representative samples of simulants (provided by manufacturers, PIs);
- Distributes simulants to Approved Characterization Labs for analysis;
- Collects and organizes characterization data on simulants provided by Approved Characterizations Labs, manufacturers, PIs;
- Provides representative samples of simulant for controversial issues;
- Recommends consultants and sources of simulants to PIs; and
- Maintains and provides access to information regarding simulants:
 - a. Characterization database
 - b. Bibliography
 - c. Set of characterization standards and procedures
 - d. Set of production procedures

4. Approved Characterization Labs:

- Define procedures for measuring the simulant property and standards for reporting the data (particular to the laboratory); and
- Measure simulant properties and report data to the Simulant Curator.

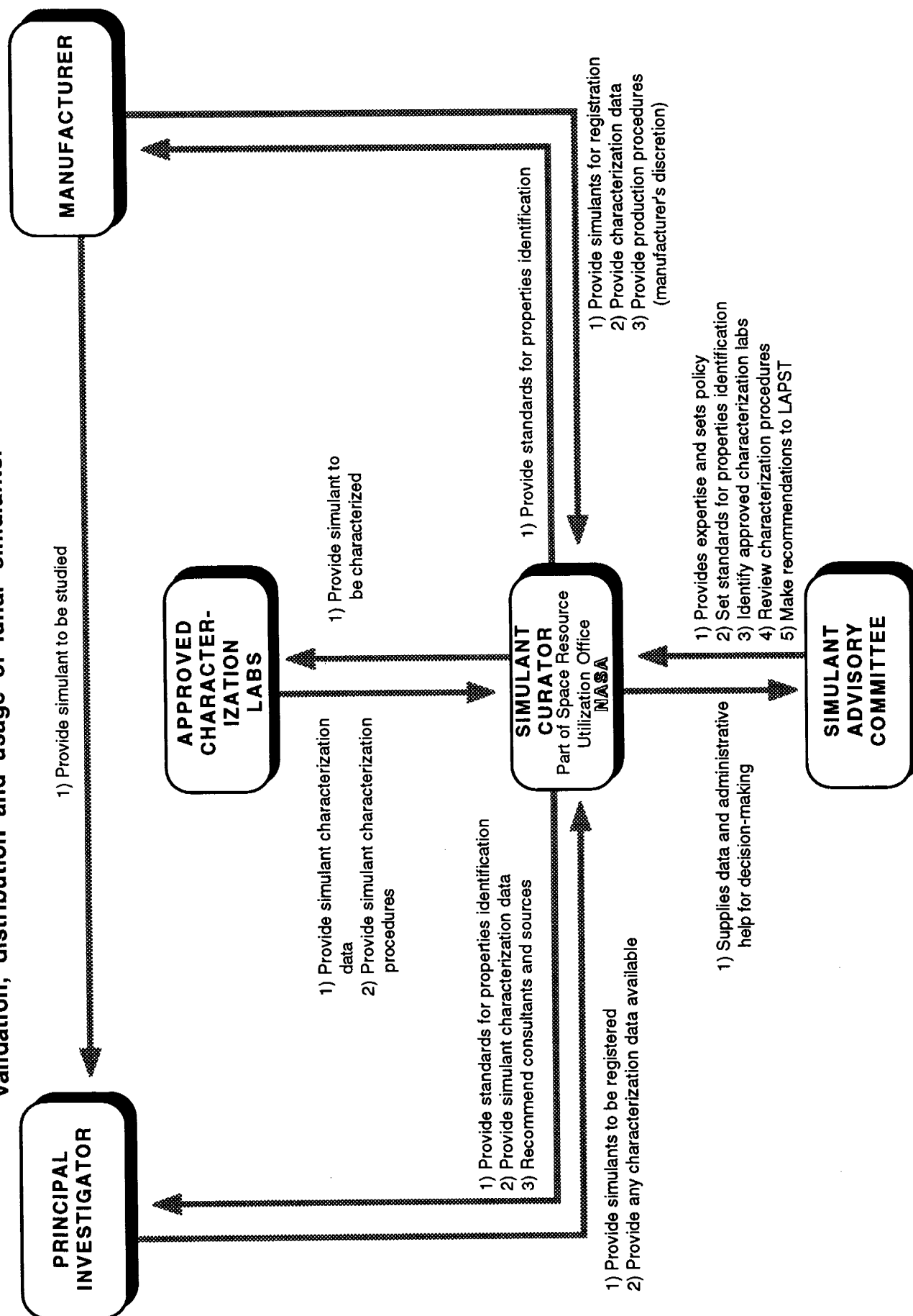
5. Manufacturers:

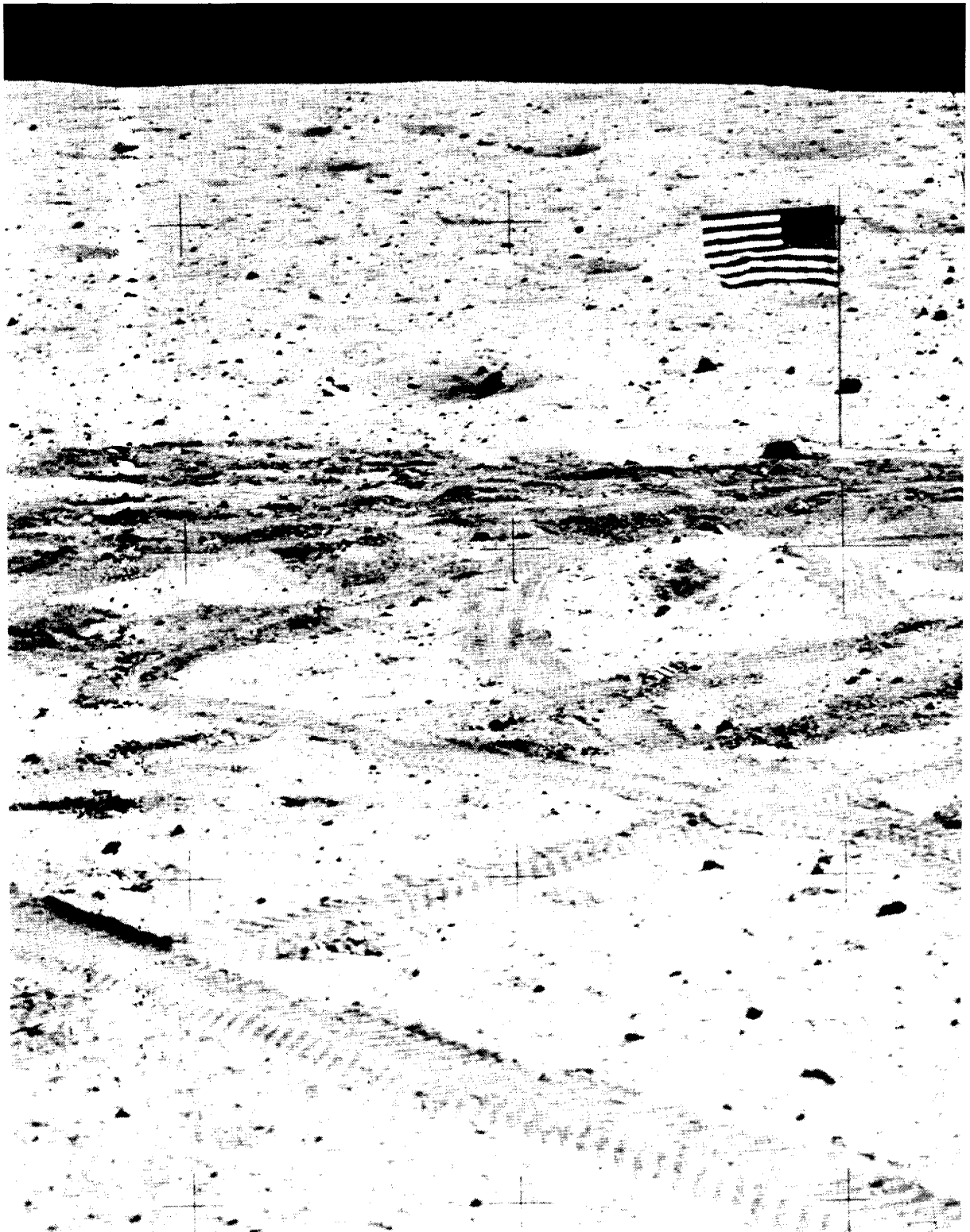
- Provide simulants to PIs;
- At manufacturer's discretion, register simulant with Simulant Curator;
- Using approved procedures, characterize simulant and provide characterization data to Simulant Curator for registered simulants; and
- Document production procedures for registered simulants and provide procedures to Simulant Curator.

6. Lunar Sample Curator:

- Reviews quality of simulant curation.

Fig. 5. Interactions of participants concerned with production, testing, validation, distribution and usage of lunar simulants.





NASA PHOTO NO. AS-16-116-18575

VI. RECOMMENDATIONS

1. It is strongly recommended that lunar simulant components be produced and made available to researchers as soon as possible.
2. The Mission Science and Technology Office should immediately designate a lunar Simulant Curator and establish a lunar simulant advisory committee.
3. Every effort should be made to assist the research community with appropriate knowledge transfer concerning the feasibility and design of specific experiments requiring simulants.

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VIII. GLOSSARY

Agglutinate - A fragile, irregularly shaped particle composed of lithic, mineral, and glass fragments welded together by glass splashes from micrometeorite impacts. Usually less than 1-2 mm diameter. Since micrometeorite impacts affect only the uppermost soil grains, agglutinates are an indicator of surface exposure, or maturity. Thus, they also contain implanted solar wind gases such as hydrogen.

Angle of repose - The maximum angle of slope, measured from horizontal, at which loose, cohesionless material will come to rest on a pile of similar material. The terrestrial angle of repose commonly ranges from 33° to 37°.

Anorthosite - A plutonic rock composed almost entirely of plagioclase feldspar. Plagioclase in terrestrial anorthosite ranges from the more sodic andesine to the more calcic bytownite. However, the lunar anorthosite is almost entirely the calcic plagioclase anorthite (CaAl₂Si₂O₈).

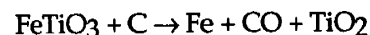
Bulk density - Mass of a material divided by its volume, including the volume of pore spaces. The *in situ* bulk density of lunar soils, as measured in Apollo core samples, ranges from 1.4 to 1.9 g/cm³.

Bulk soil pyrolysis - Extraction of solar-wind-implanted gases such as He, H₂, N₂, and CO from bulk lunar soil by heating to about 700°C.

Carbonyl process - A method of isolating and purifying iron and/or nickel by using CO to form Fe(CO)₅ or Ni(CO)₄. This is followed by a decomposition step at a higher temperature to precipitate the pure metal.

Carbothermal reduction - A method of releasing oxygen from lunar

oxides/silicates by reacting it with carbon to first form the compound CO. For example, ilmenite feedstock can be mixed with a carbon reductant and an anorthite fluxing agent and melted, causing the following endothermic reaction:



The CO may then be dissociated to form oxygen and carbon. Other minerals, such as olivine and pyroxene, may be treated in the same general way.

Cohesion - Shear strength in a sediment not related to interparticle friction.

Compressive strength - The maximum compressive stress that can be applied to a material before failure occurs.

Devitrification - Conversion of the glassy texture of a rock to a crystalline texture after solidification.

Fatigue - Failure of a material after many repetitions of a stress that of itself is not strong enough to cause failure.

Ferric iron - Iron in the +3 oxidation state; an iron atom that has lost 3 electrons, resulting in a +3 electrical charge.

Ferroan anorthosite - The mafic minerals in the ferroan anorthosite are relatively enriched in Fe compared to high-Mg anorthosites. The ferroan anorthosites are more abundant Moon-wide. A simulant for lunar ferroan anorthosite may be found in the Stillwater complex, Montana, a layered intrusion that also contains an analog for high-Mg anorthosite.

Fluoride flux electrolysis - A variant of the magma electrolysis process. Releases oxygen from lunar bulk soil by using molten fluoride salts to enhance yield and lower required temperatures.

Friable - Easily broken or reduced to a powder (applied to rock or mineral).

Glass reduction - Processing of the metal oxide component of the glassy part of lunar soil. A reducing agent such as H_2 or C is used to form an intermediate compound, which can then be further processed to release O_2 .

High-Mg anorthosite - The mafic minerals in the high-Mg anorthosite are relatively enriched in Mg compared to ferroan anorthosites. A simulant for lunar high-Mg anorthosite may be found in the Stillwater complex, Montana, a layered intrusion that also contains an analog for ferroan anorthosite.

High-Ti mare basalt - Lunar mare basalts that contain 9 to >13% TiO_2 are classified as high-Ti mare basalts.

Highlands - The light-colored, older, more cratered lunar terrain at higher elevation, which is relatively enriched in calcium and aluminum.

Hydrous phases - Mineral phases formed as a result of reaction with water.

Ilmenite - This iron-black mineral is the most abundant opaque mineral found in lunar rocks, mostly in mare basalts, and with compositions near $FeTiO_3$. Most lunar ilmenite contains some Mg (zero to 5-6% MgO by weight.). Although terrestrial ilmenite almost always contains some Fe^{+3} , lunar ilmenite contains none. Reduction of this mineral is being studied to produce oxygen (see ilmenite reduction).

Ilmenite reduction - A method of extracting oxygen from the mineral ilmenite ($FeO \cdot TiO_2$). A reducing agent such as H_2 , C, etc. is reacted with the mineral to form H_2O or CO , etc., which can then be separated (by electrolysis,

for example) into oxygen and reductant, after which the reductant is recycled to be used in the process again.

Immature - Characteristic of a soil that has been exposed on the uppermost lunar surface for a relatively short time (see Maturity).

Implanted solar particle - Atomic nuclei from the sun (see Solar flare and Solar wind) that impinge on grains with enough energy to become implanted in the silicate structure. The most common nucleon is hydrogen, but other useful volatiles such as He, C, and N are also implanted.

ISSP - Acronym for in-flight sustained shockwave plasma. An ISSP reactor at the University of Minnesota consists of a hollow, central cathode radially surrounded by six anodes. Arc rotation of 1000-3000 rpm maintains the shockwave plasma in a rotating, homogeneous magnetic field. Crushed rock is injected in the plasma and partially melted, forming agglutinate-like products and other glasses.

KREEP - Acronym for potassium (K), rare earth elements (REE), and phosphorus (P). These elements are relatively enriched in the Fra Mauro region (Apollo 14 site) of the Moon.

Lithology - The physical character (color, structure, mineralogy, and grain size) of a rock.

Low-Ti mare basalt - Lunar mare basalts that contain 0.5 to 6% TiO_2 are classified as low-Ti mare basalts. The classification can be divided into low and very low-Ti mare basalts.

Lunar simulant - Any material manufactured from natural or synthetic terrestrial or meteoritic components for the purpose of simulating one or more physical and/or chemical properties of a lunar rock or soil.

Magma electrolysis - Electrolysis of molten silicate carried on at 1800-2000 K in which O_2 forms at the anode and a molten ferro-silicon phase forms at the cathode. Possible method of lunar oxygen production.

Mare (plural is maria) - The dark-colored, younger, smoother lunar terrain at lower elevation, which is relatively enriched in iron and magnesium.

Mature - Characteristic of a soil that has been exposed on the uppermost lunar surface for a relatively long time (see Maturity).

Maturity - Relative length of exposure time of soil grains on uppermost lunar surface. While on the surface grains are exposed to micrometeorite impacts and solar wind and solar flares (see Solar wind, Solar flare). Thus, indicators of soil maturity include (1) the concentration of single-domain metallic iron (see Single-domain Fe), (2) abundance of agglutinates, and (3) the concentration of implanted solar gases such as H and He.

Modal composition - The mineral composition of a rock, usually expressed in weight or volume percentages.

Olivine - A silicate mineral that displays a solid solution series between Mg_2SiO_4 (Forsterite) and Fe_2SiO_4 (Fayalite).

Permeability - Capacity of a porous rock or soil for transmitting a fluid (gas or liquid).

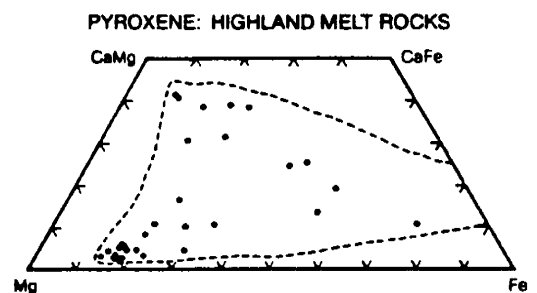
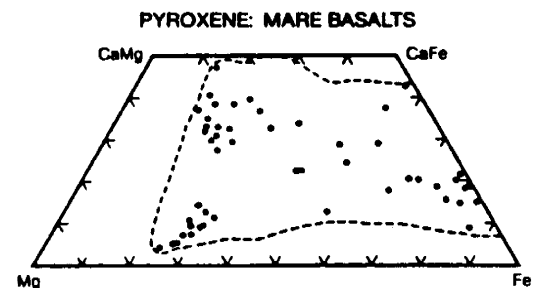
Plagioclase - A feldspar mineral which displays a solid solution series between $NaAlSi_3O_8$ (albite, abbreviated Ab) and $CaAl_2Si_2O_8$ (anorthite, abbreviated An). Compared to terrestrial plagioclases, the lunar plagioclases are more calcic and less diverse. Plagioclase found in mare regions ranges from An 74 to 98 mole % compared to Ab. Highlands plagioclases

are even more calcic, ranging from An 90 to 99. Most of the white material observed in lunar rocks is plagioclase.

Porosity - Percentage of the bulk volume of a rock or soil occupied by interstices.

Pyroclastic - Pertaining to clastic rock material formed by volcanic explosion. Lunar pyroclastic desposits often consist of glass spheres, thought to be formed in a "fire fountain."

Pyroxene - A group of dark silicate minerals having the general formula $ABSi_2O_6$ where A= Ca, Na, Mg, or Fe+2 and B= Mg, Fe+2, Fe+3, Cr, Mn, or Al, with Si sometimes partly replaced by Al. Lunar pyroxenes exhibit a range of compositions as shown in this quadrilateral diagram with the major A, B combinations shown at the corners (Taylor, 1990b).



Regolith - The layer or mantle of fragmental, incoherent, unconsolidated rocky material that overlies bedrock.

Rheology - Deformation and flow of matter.

Shear strength - Resistance of a body to shear stress.

Simulant - See Lunar simulant.

Single-domain Fe - Single magnetic domain. In lunar regolith particles, single-domain iron is descriptive of the tiny metallic iron grains dispersed throughout the glassy phases produced by micrometeorite impacts in the presence of implanted solar protons.

Soil - Lunar soil is the <1-cm portion of the regolith.

Solar flare - Nuclei sporadically ejected from the sun that strike the lunar surface at 1-100 MeV/nucleon and penetrate about 1 mm into regolith grains. Nuclei in the iron group ($Z = 18$ to 28) can leave tracks in silicates. The solar flare proton flux striking the Moon averaged for those protons >10MeV over 1 m.y. is about 100 per cm^2 per sec.

Solar wind - Nuclei, mostly protons (hydrogen), with ~10% alpha particles (helium), ejected from the sun that strike the lunar surface at ~1 KeV/nucleon and penetrate only ~ 100 Å into regolith grains. The proton flux is about 10^8 per cm^2 per sec.

Surface area - The area of the outer surface of grains. For a bulk particulate solid, surface area increases as grain size decreases. Grain shape, pore size, and chemical activity are also factors. Quantitative values for surface area vary with the method used to measure it (a matter of scale). Methods that measure particle or pore size cannot be compared with surface areas measured by the

amount of gas that can be absorbed as a monolayer.

Tensile strength - Maximum applied tensile stress that a body can withstand before failure. Tensile stress is the stress that tends to pull a body apart.

Tribology - The study of interacting surfaces in relative motion; friction.

APPENDIX A.

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APPENDIX B.

***Production of Glass and Agglutinates
in an In-Flight Sustained Shockwave Plasma Reactor***

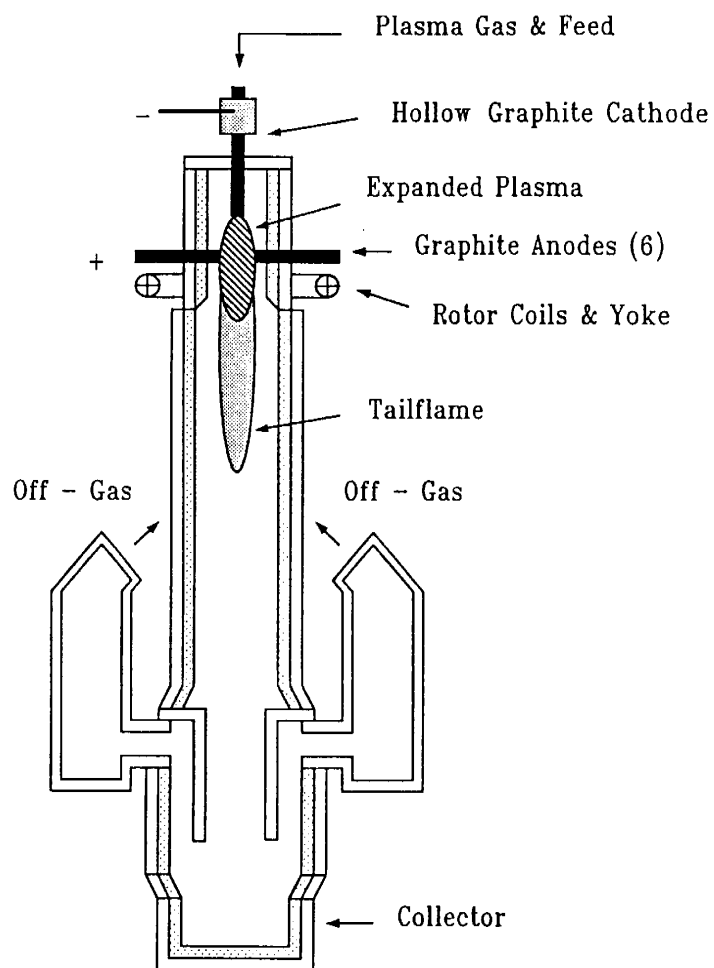


Fig. B1. Schematic of an ISSP reactor.

APPENDIX B

Production of Glass and Agglutinates in an In-Flight Sustained Shockwave Plasma Reactor

It has been demonstrated that plasma melting is a viable method for producing simulants for the glassy components of the lunar soil (Weiblen *et al.*, 1990). The technique has been evaluated using an in-flight sustained shockwave plasma (ISSP) reactor at the Mineral Resources Research Center at the University of Minnesota (Fig. B1). The 10-m-tall reactor consists of a cylindrical stainless steel arc chamber lined with refractory material mounted above additional refractory-lined sections that provide a free-fall zone and collector at the bottom. The arc chamber consists of a vertical, hollow, water-cooled graphite cathode that is radially surrounded by the arc plasma gas (argon or nitrogen). Sample materials are fed through the hollow cathode. Arc rotation, produced by utilizing the principle of the DC motor, maintains the shockwave plasma in a rotating, homogeneous magnetic field in the plane of the anodes. Rotational speeds have been measured in the range of 1000 to 3000 rpm, depending on the operating conditions (Reid *et al.*, 1987). This reactor was operated at 400 amp and 150 to 250 V to test the effect of the plasma processing on a basalt feedstock. Run products with 10 to 30% glassy material were achieved with feed rates of 40 to 50 kg/hr. Runs to date have been with argon as the plasma gas and no gases to control the oxidation state of the atmosphere in the plasma, free-fall zone, or collector. Run products consisted of unreacted mineral fragments, massive, globular glass, and vesicular glass in a variety of textures that resemble the glassy components of lunar soils (Fig. B2). The glass also contains immiscible native iron blebs analogous to lunar glasses. However, iron-titanium oxide phases, probably with some ferric iron, also occur in the glass and it is not clear if single-domain iron is present. The proportions of these components depended on the power, grain size, and rate of grain feed through the hollow cathode. The principal chemical difference between the feed and the run products under these conditions has been the reduction of the water content of the glass by an order of magnitude to 0.06 wt%. This plasma process is being further refined in an attempt to more closely simulate the chemical, mineralogical, and textural features of lunar soils.

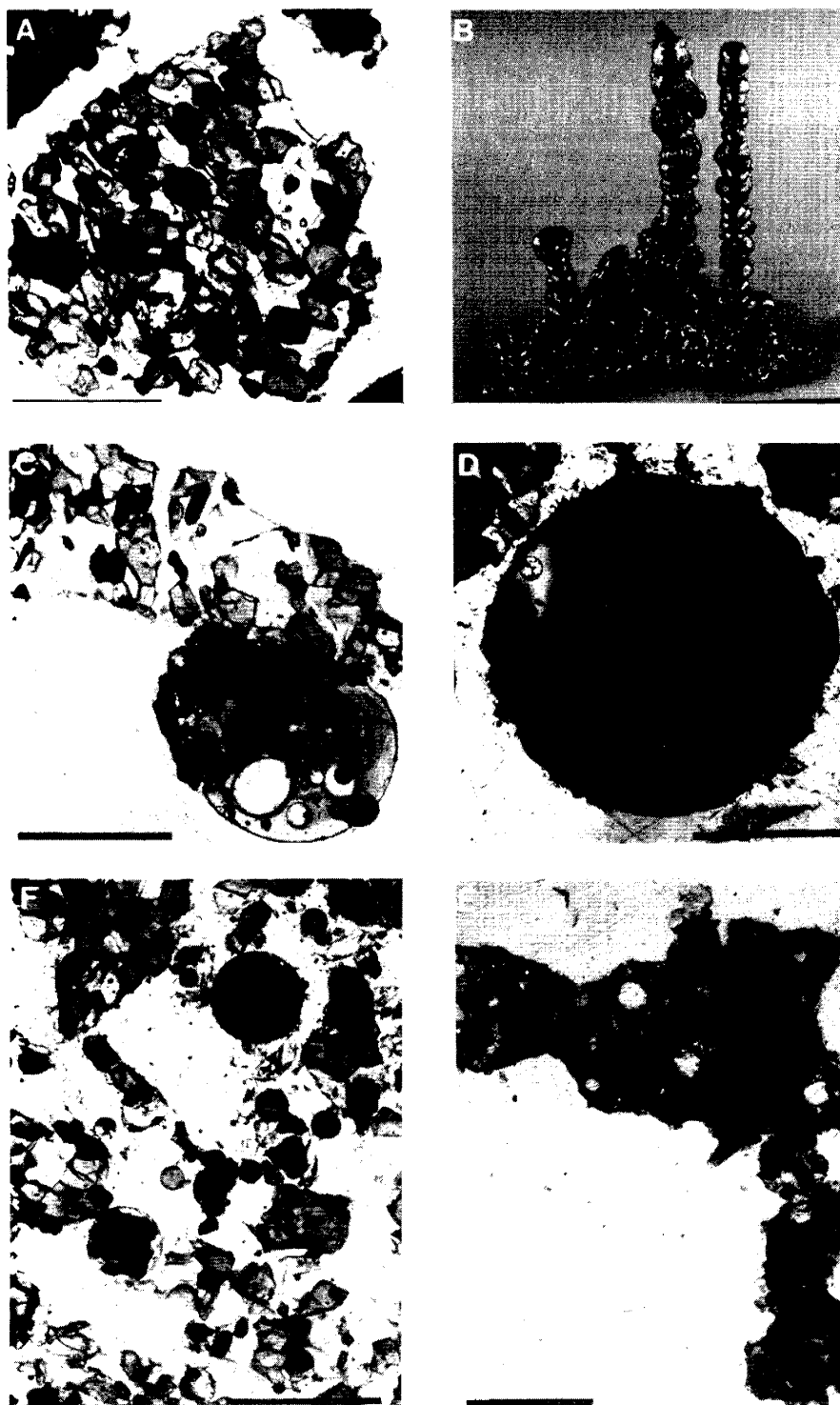


Fig. B2. Run products from a <1.5-mm fraction of basalt processed in the ISSP reactor.

APPENDIX C.

Issue Definition Sheets

ISSUE DEFINITION SHEETS

Comments by Workshop Participants

TOPIC	AUTHOR	PAGE
Policy and Organization:		
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ITBC FORM

Issues to be Considered

Issue:

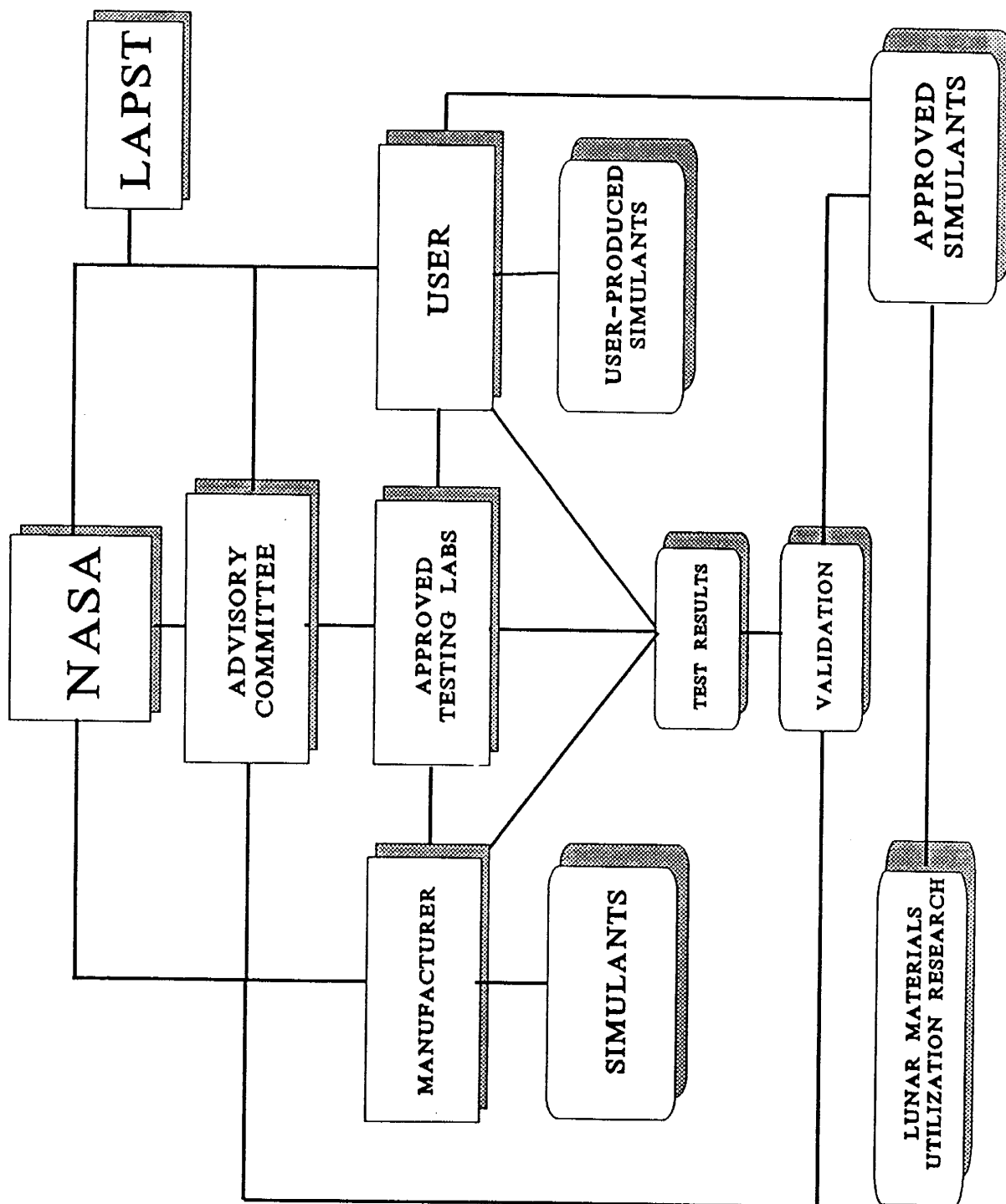
How shall the simulant production, testing, and distribution be organized?

Possible Resolution:

See attached organizational chart. This chart represents the status of organizational planning at the close of the workshop. The discussion of organizational matters was incomplete at that point in time.

Name: Workshop attendees

Organization:



ITBC FORM

Issues to be Considered

Issue:

How shall the production and use of simulants be facilitated?

Possible Resolution:

A Lunar Simulant Curator, working with the Simulant Advisory Committee, fulfills the need for a dedicated NASA organization to be the focal point for simulant concerns.

Two organizational plans are presented. In one plan, which emphasizes high-quality data, the Simulant Curator (NASA) plays a central and controlling role. In the other plan, which emphasizes timeliness and convenience for the simulant user (PI), the PI plays a central role. **The plan in which the Simulant Curator plays a central role is recommended, particularly if the number of PIs using simulants is greater than 8-10, because the Curator's controlling function assures the collection of more complete and better-quality data for use by all those interested in lunar simulants.**

Name: Claire Dardano and Judy Allton

Organization:

Lockheed Engineering & Sciences Company

PROPOSAL FOR DISTRIBUTION, CHARACTERIZATION, and CURATION OF LUNAR SAMPLE SIMULANTS

	CURATOR-CENTERED MODE	PI-CENTERED MODE
ADVANTAGES	<ol style="list-style-type: none"> 1. Provides a permanent and dedicated single point of contact for establishing communication among PIs, manufacturers, and the Simulant Advisory Committee (SAC). 2. Provides a single-point mechanism for characterizing simulants, documenting the results, and making them available to PIs and manufacturers. 3. Assures LAPST and others that characterization is done on registered simulants and that the data are documented and made available. This results in more data of higher quality accessible to anyone interested. 4. Gives approved labs incentive to produce procedures and prepare for doing the analytical work. This plan implies that NASA will financially support curation and characterization analyses at an identifiable level. 5. Assures that all PIs are treated more equally in requesting characterization analyses from laboratories, rather than labs doing favors for colleagues. 6. This mode does not preclude direct interaction between users and manufacturers or laboratories. 	<ol style="list-style-type: none"> 1. Gives the user more control over obtaining characterization analyses. Lets the user exert creativity, energy and influence to accomplish goals. Implies the users will pay for characterization analyses. 2. Provides the potential for greater timeliness in obtaining characterization analyses and reduced requirements for documentation by eliminating the curator as a middleman.
DISADVANTAGES	<p>This mode has the potential disadvantage of being more time consuming during transactions routed through the Curator instead of directly between other participants.</p>	<p>The principal disadvantage to the entire lunar simulant user community for this mode of operation is the potential degradation of the dataset available. Experience with lunar sample curation has shown that many PIs have a poor record of forwarding data to the curator. This implies that the compiled characterization database may be unnecessarily incomplete. In addition, this mode places the burden of requesting and gathering characterization data onto the PI.</p>

LUNAR SAMPLE SIMULANT PARTICIPANTS Responsibilities for Curator-Centered Mode

Differences from PI-Centered mode are italicized.

A. Simulant Advisory Committee (SAC)

1. Provides expertise and sets policy
2. Serves as a liaison between producers and PIs; recommends simulant sources
3. Defines standards for simulant properties and identifies approved labs for characterizing these properties
4. Reviews procedures written by Approved Characterization Labs for measuring properties of simulants.
5. Educates new PIs and producers about properties and sources of simulants
 - a. Provides and/or recommend consultants
 - b. Conducts workshops

B. Principal Investigators

1. Procure or manufacture simulants
2. *Request analysis by Approved Characterization Labs via the Simulant Curator*
3. Provide Simulant Curator with representative sample and *any available* characterization data for registered simulants

C. Simulant Curator

1. Serves as an administrative agent for the SAC and a single point of contact for PIs with a permanent location and dedicated staff
2. Archives representative samples of simulants (provided by manufacturers, PIs)
 - a. Physical storage of samples
 - b. Maintains inventory database
 - c. Develops and maintains processing procedures
3. Distributes simulants to Approved Characterization Labs for analysis
4. Collects and organizes characterization data on simulants provided by *Approved Characterization Labs*, manufacturers, PIs
5. Provides representative samples for controversial issues
6. Recommends consultants to PIs
7. Produces catalogs
8. Maintains and provides access to information regarding simulants
 - a. Characterization database
 - 1) General descriptions
 - 2) Specific laboratory data (format of each characteristic determined by characterization lab)
 - b. Bibliography
 - 1) Distributes copies of available publications
 - 2) Recommends sources for nonavailable publications
 - c. Set of characterization standards and procedures
 - d. Set of production procedures

D. Approved Characterization Labs

1. Define procedures for measuring the simulant property and standards for reporting the data (particular to the laboratory)
2. Measure simulant properties and report data to the Simulant Curator

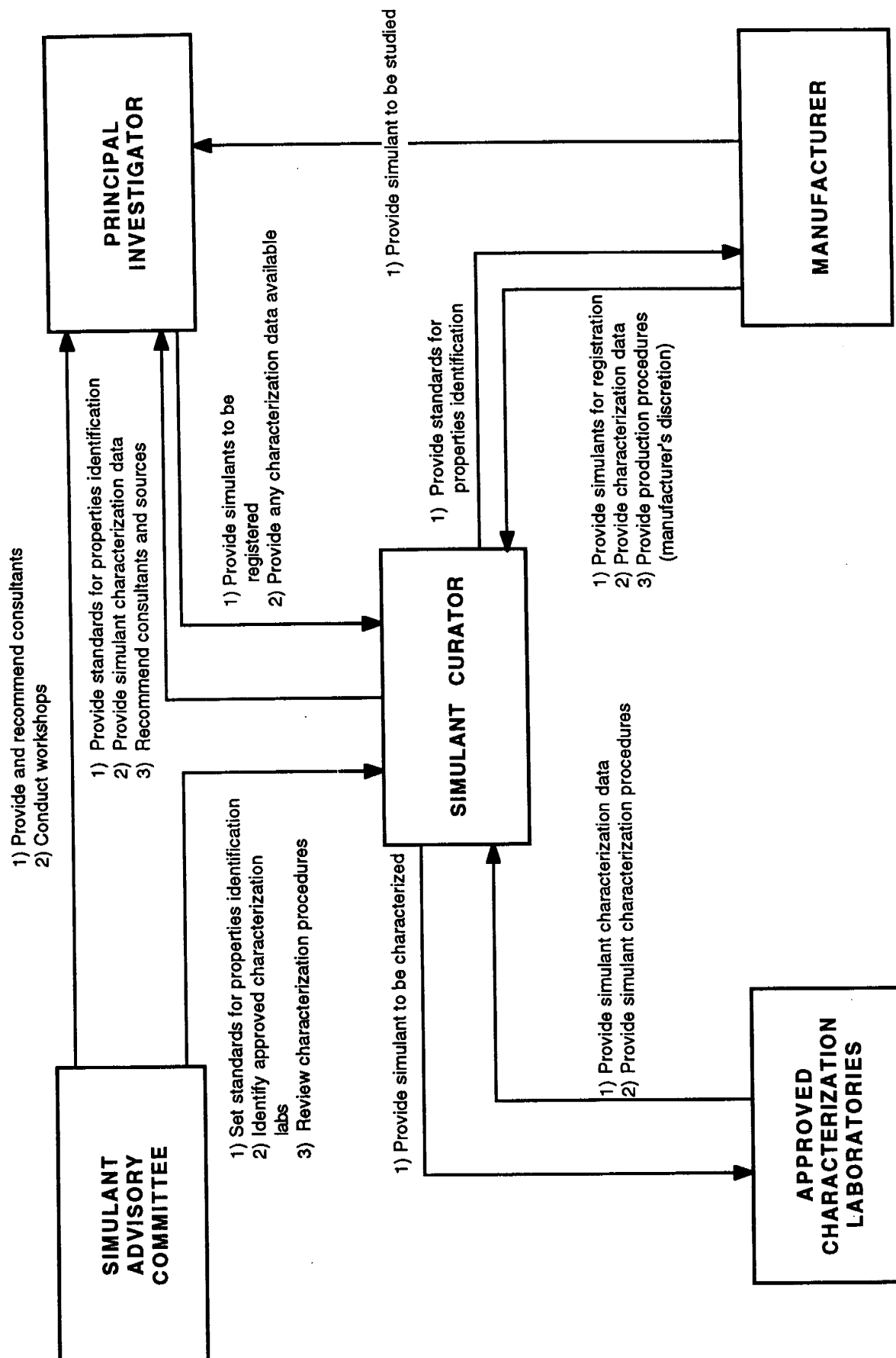
E. Manufacturers

1. Provide simulants to PIs
2. At manufacturer's discretion, register simulants with the Simulant Curator
3. Using approved procedures, characterize simulant and provide characterization data to Simulant Curator for registered simulants
4. Document production procedures for registered simulants; provide procedures to Simulant Curator

F. Lunar Sample Curator

1. Reviews quality of simulant curation

LUNAR SAMPLE SIMULANT PARTICIPANT INTERACTION Curator-Centered Mode



LUNAR SAMPLE SIMULANT PARTICIPANTS Responsibilities for PI-Centered Mode

Differences from Curator-Centered mode are italicized.

A. **Simulant Advisory Committee (SAC)**

1. Provides expertise and sets policy
2. Serves as a liaison between producers and PIs; recommends simulant sources
3. *At the request of a user:* defines standards for simulant properties and identifies approved labs for characterizing these properties
4. Reviews procedures written by Approved Characterization Labs for measuring properties of simulants
5. Educates new PIs and producers about properties and sources of simulants
 - a. Provides and/or recommends consultants
 - b. Conducts workshops

B. **Principal Investigators**

1. Procure or manufacture simulants
2. *Have simulants characterized by an approved lab or obtain approved laboratory procedures to characterize simulants*
3. Provide Simulant Curator with representative sample, characterization data, and characterization procedures for registered simulants (*principal agent responsible for these activities*)
4. *Initiate contact with SAC; request definition of standards and identification of an approved lab for specified properties*

C. **Simulant Curator**

1. Serves as administrative agent for SAC with permanent location and staff
2. Archives representative samples of simulants (provided by manufacturers, PIs)
 - a. Physical storage of samples
 - b. Maintains inventory database
 - c. Develops and maintains processing procedures
3. Collects and organizes characterization data on simulants provided by manufacturers, PIs
4. Provides representative samples for controversial issues
5. Recommends consultants to PIs
6. Produces catalogs
7. Maintains and provides access to information regarding simulants
 - a. Characterization database
 - 1) General descriptions
 - 2) Specific laboratory data (format of each characteristic determined by characterization lab)
 - b. Bibliography
 - 1) Distributes copies of **available publications**
 - 2) Recommends sources for **nonavailable publications**
 - c. Set of characterization standards and procedures
 - d. Set of production procedures

D. Approved Characterization Labs

1. Define procedures for measuring the simulant property and standards for reporting the data (particular to the laboratory)
2. Provide the measurement procedures and reporting standards *to the SAC via Simulant Curator for approval*
3. *Measure simulant properties and report data and procedures to user.*

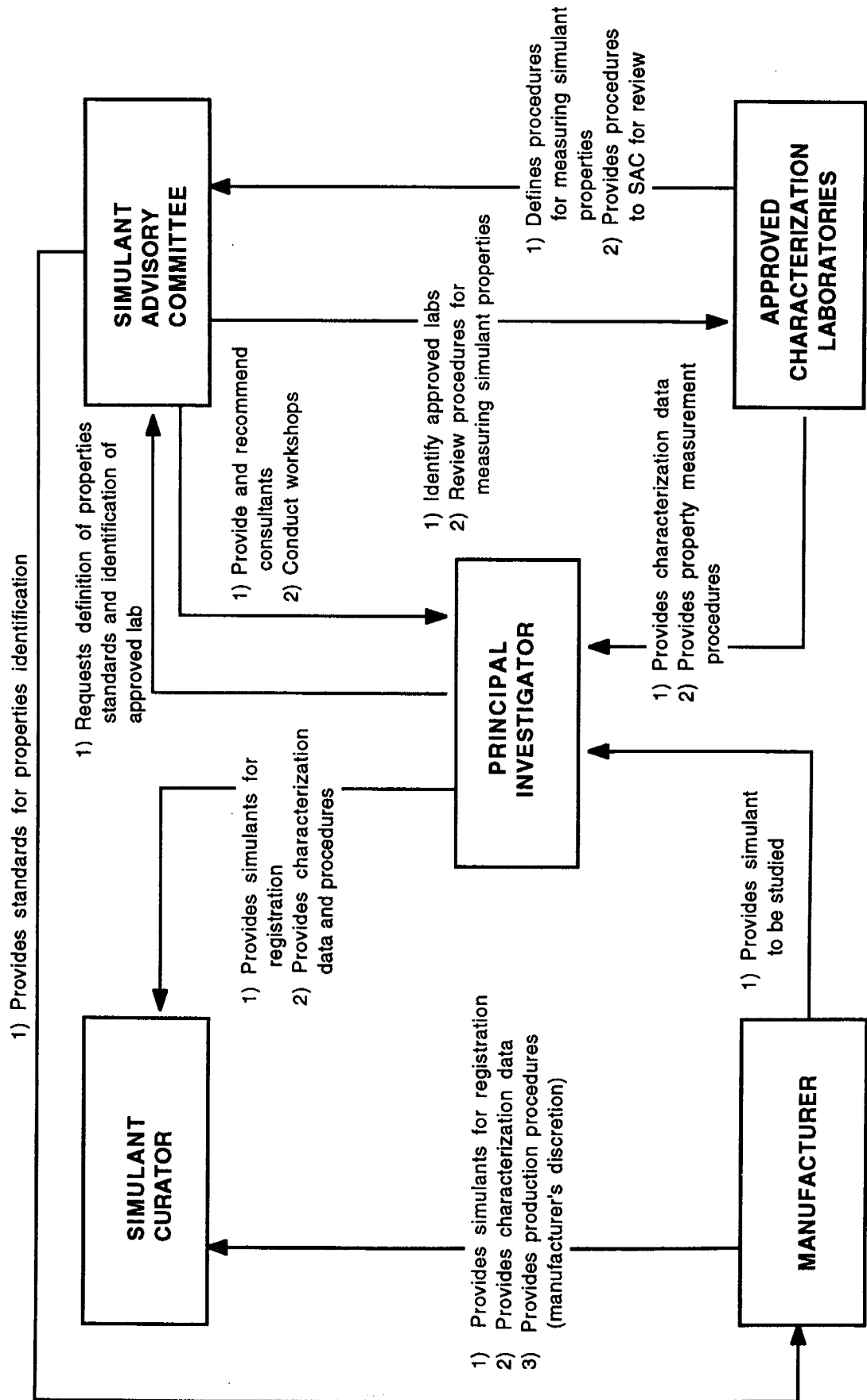
E. Manufacturers

1. Provide simulants to Pls
2. At manufacturer's discretion, register simulants with the Simulant Curator
3. Using approved procedures, characterize simulant and provide characterization data and procedures to Simulant Curator for registered simulants
4. Document production procedures for registered simulants; provide procedures to Simulant Curator

F. Lunar Sample Curator

1. Reviews quality of simulant curation

LUNAR SAMPLE SIMULANT PARTICIPANT INTERACTION **PI-Centered Mode**



ITBC FORM

Issues to be Consideréd

Issue:

How much should LAPST become involved in helping users to define experiments?

Possible Resolution:

LAPST, as judge of an experiment's merit in allocating lunar samples, should not become involved in helping users to define experiments. A separate committee of lunar material experts (planetary scientists and geotechnical engineers) and lunar outpost application experts (engineering and biological applications) should be created to assist users in defining experiments and obtaining appropriate simulant.

Name: Judy Allton

Organization:

Lockheed Engineering & Sciences Company

ITBC FORM

Issues to be Considered

Issue:

POLICY: Lunar Simulants Validation

Need validation of characteristics of any lunar soil simulant or lunar feedstock simulant that is manufactured by anybody. A reproducible simulant is needed so that different experimenters can produce results that can be accurately compared and contrasted. This manufacture will probably not be a FOR-PROFIT operation because mass production of a single simulant at low cost to meet all needs is unrealistic.

Possible Resolution:

Peer review of individually produced simulant. A sample of any simulant produced by anybody is sent to another researcher in the same general field. That second researcher independently verifies that the qualities claimed for it do in fact exist. A NASA person could then operate as a *Moderator* to the process. The NASA moderator can monitor the process, help negotiate disputed issues, etc. The system would be an analog to the publication process:

NASA Moderator <--- Journal Editor

Simulant Manufacturer <--- Manuscript Author

Other investigator <--- Reviewer

The advantage is that anyone who needs a simulant can produce their own or procure it from wherever, without having to get it through a NASA-designated manufacturer. This should reduce red tape and should also be faster than "channels." Also, the various researchers will be intimately familiar with each other's simulants.

Name: Bonnie Cooper

Organization:

The University of Texas at Dallas

ITBC FORM

Issues to be Considered

Issue:

Lunar Simulant Committee

A committee of several (five or six) scientists and engineers, knowledgeable in lunar materials, should be established with specific tasks aimed at assisting NASA management in implementing the production and distribution of well-designed lunar simulants. The membership of this committee should be established by NASA management, not by LAPST; this should not result in simply adding one or two new members to LAPST. However, it should have a person(s) who is on LAPST and who can act as a liaison. This Lunar Sample SubCommittee (LSSC), through its reporting both to D. McKay and LAPST, could effect a knowledge transfer. When a request for lunar sample use comes before LAPST, LAPST will have knowledge of the prior research using lunar simulants.

Possible Resolution:

DO IT!

Name: Larry Taylor

Organization:

University of Tennessee

ITBC FORM

Issues to be Considered

Issue:

Actual production, validation*, and supply to experimenters of the "standard" simulants selected as a result of this report.

*Verifying that all critical properties fall within established (by the report?) numerical limits.

Possible Resolution:

Selection of contractors by NASA, based on the properties of the simulant types defined by the report, for supply, requiring each one to validate each shipment to a central NASA (JSC) distribution point, at which relative needs, quantities, and other matters (program priorities, etc.) would be assured.

Name: T. Triffet

Organization:

UA/NASA Space Engineering Research Center

ITBC FORM

Issues to be Considered

Issue:

Regarding the number of recommended simulants:

Of the 24 processes discussed in this workshop:

8/24 need only crushed rock (1-5).

4/24 need crushed, sieved, and sized rock (1-5).

2/24 need additional crushed glass (but not necessarily spheres or agglutinates).

So half of all the processes need only crushed and/or sieved rock of compositions 1-5.

1/24 needs crushed, sized rock with agglutinates containing single-domain Fe.

6/24 need extensively processed material, including g (special processing).

The above seven materials are not likely to be created in large amounts and may need to be tailored to particular experiments.

3/24 need mineral separates, either natural or synthetic.

Possible Resolution:

The number of simulants that needs to be created in large quantities is probably five (crushed, sieved, and sized rock of the five different compositions discussed). It is probably not necessary to maintain a large amount of simulant containing glass and/or agglutinates, because the processes requiring this material seem to have additional requirements, which are not easily produced in bulk.

Name: Melinda Hutson

Organization:

University of Arizona

ITBC FORM

Issues to be Considered

Issue:

Beneficiation testing should be carried out *now* using lunar soils. This is essential for the following reasons:

1. NASA must know what can be separated from lunar soils using practical means before embarking on a costly exercise of soils processing--no matter what the utilization method! Beneficiation testing will reveal important effects, such as soil degradation, which will affect all utilization technologies--in spite of claims to the contrary.
2. A knowledge of the mix of *recovered* soil components and their chemistries is essential in designing *meaningful* simulants for use in large-scale testing here on Earth. Even if the utilization technologies are not originally visualized to use beneficiated soils, surely testing will be carried out with different levels of soil contaminants for the purpose of testing process sensitivities. Beneficiation is an ideal way to get a realistic blend of natural contaminants. Beneficiation testing on soils of interest is the most direct route to this information. (See attached information on modal and chemical analysis of production of magnetic separation of mare soil 71061.)
3. Information on beneficiation of lunar soils will be needed in carrying out engineering evaluations and comparisons of alternative utilization technologies that require differing levels of beneficiation.
4. I doubt that a simulant that will be useful in testing beneficiation technology can be produced within one to two years. [See comparison of Magnetic Spectra of Minnesota Lunar Simulant (as supplied by Space Studies Institute) and mare soil 10084 upon which it was designed.]

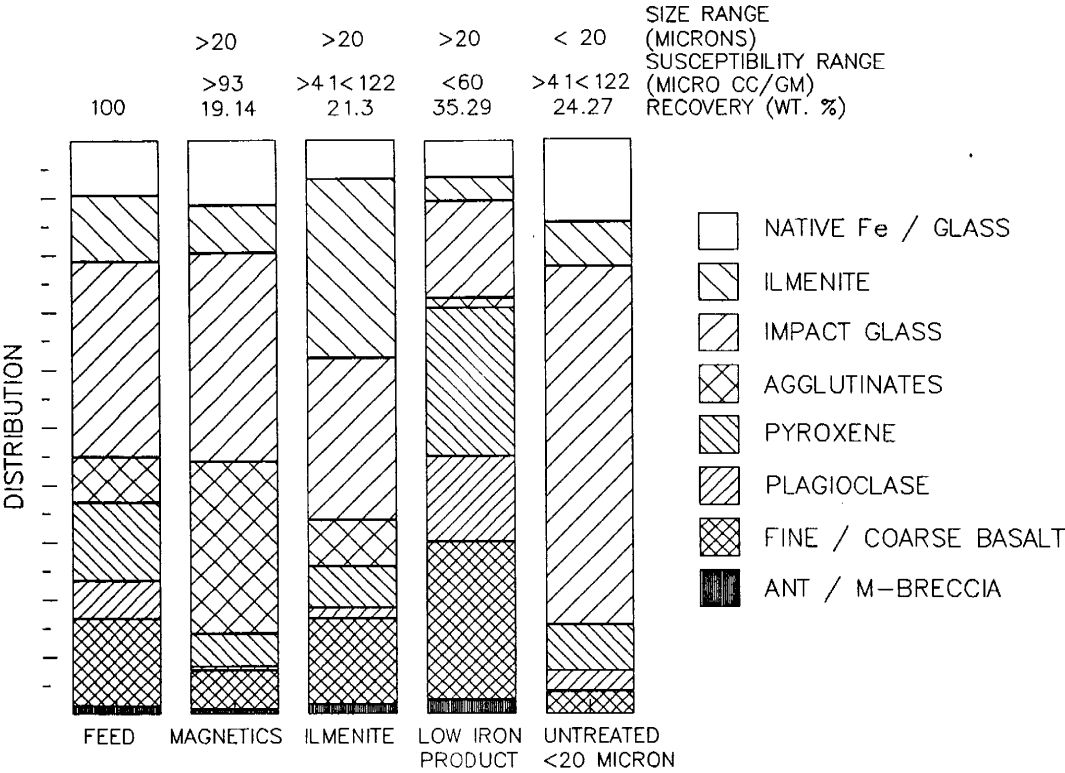
Possible Resolution:

Name: Robin R. Oder

Organization:

EXPORTech Company, Inc.

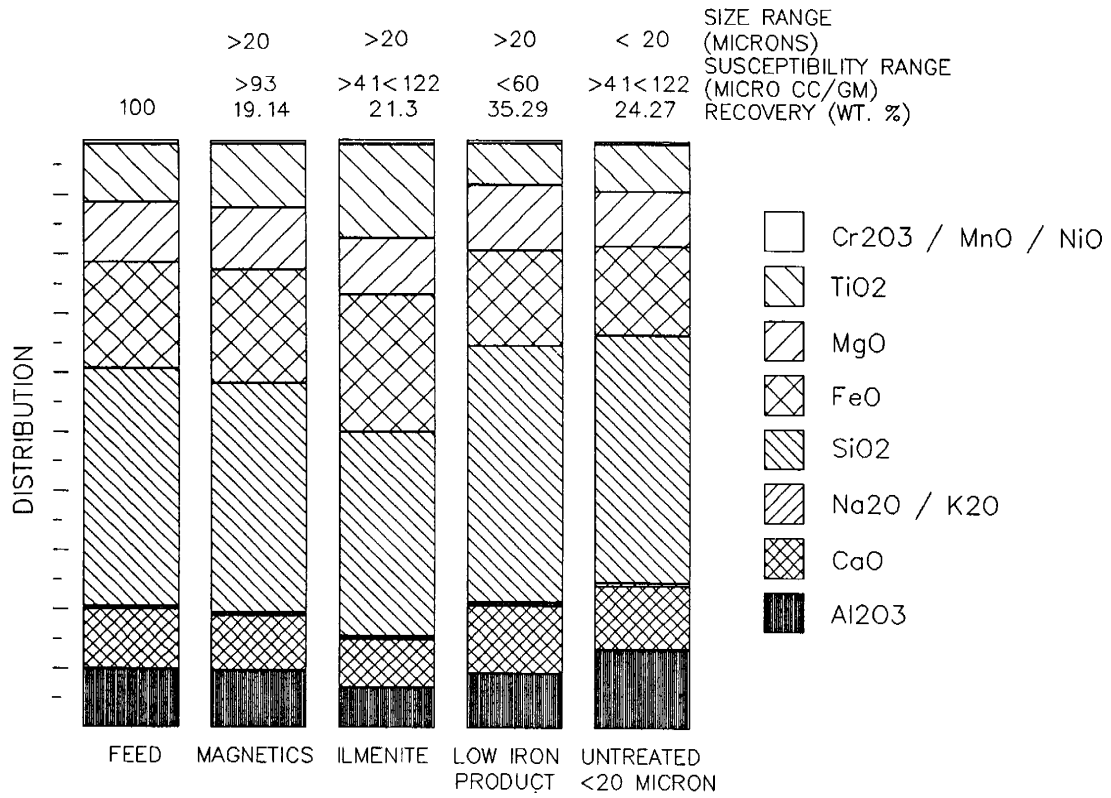
ILMENITE FLOW SHEET
LUNAR SOIL 71061



ILMENITE FLOW SHEET
Lunar Soil 71061

Size Range (Microns)		< 20	> 20	> 20	< 20
Susceptibility Range (Micro cc/gm)		> 93	> 41 < 122	< 60	> 41 < 122
Recovery (wt%)	100	19.14	21.3	35.29	24.27
	<u>Feed</u>	<u>Magnetics</u>	<u>Ilmenite</u>	<u>Low Iron Product</u>	<u>Untreated < 20 Micron</u>
ANT	0.3	0.1	0.1	0.7	0.0
M-Breccia	1.2	0.8	1.7	1.8	0.0
Fine Basalt	7.0	4.0	6.6	10.8	4.0
Coarse Basalt	8.2	2.8	8.3	16.7	0.0
Plagioclase	6.6	0.7	1.9	14.8	3.6
Pyroxene	13.6	5.7	7.2	25.8	7.9
Ilmenite	11.6	8.4	31.3	4.2	7.8
Agglutinates	8.0	29.9	8.0	1.7	0.0
Impact Glass	34.0	36.3	28.1	16.9	62.3
Native Fe	2.7	2.3	0.5	0.3	8.3
Orange Glass	5.4	6.3	4.6	4.6	6.4
Brown Glass	1.4	2.7	1.7	1.5	0.0

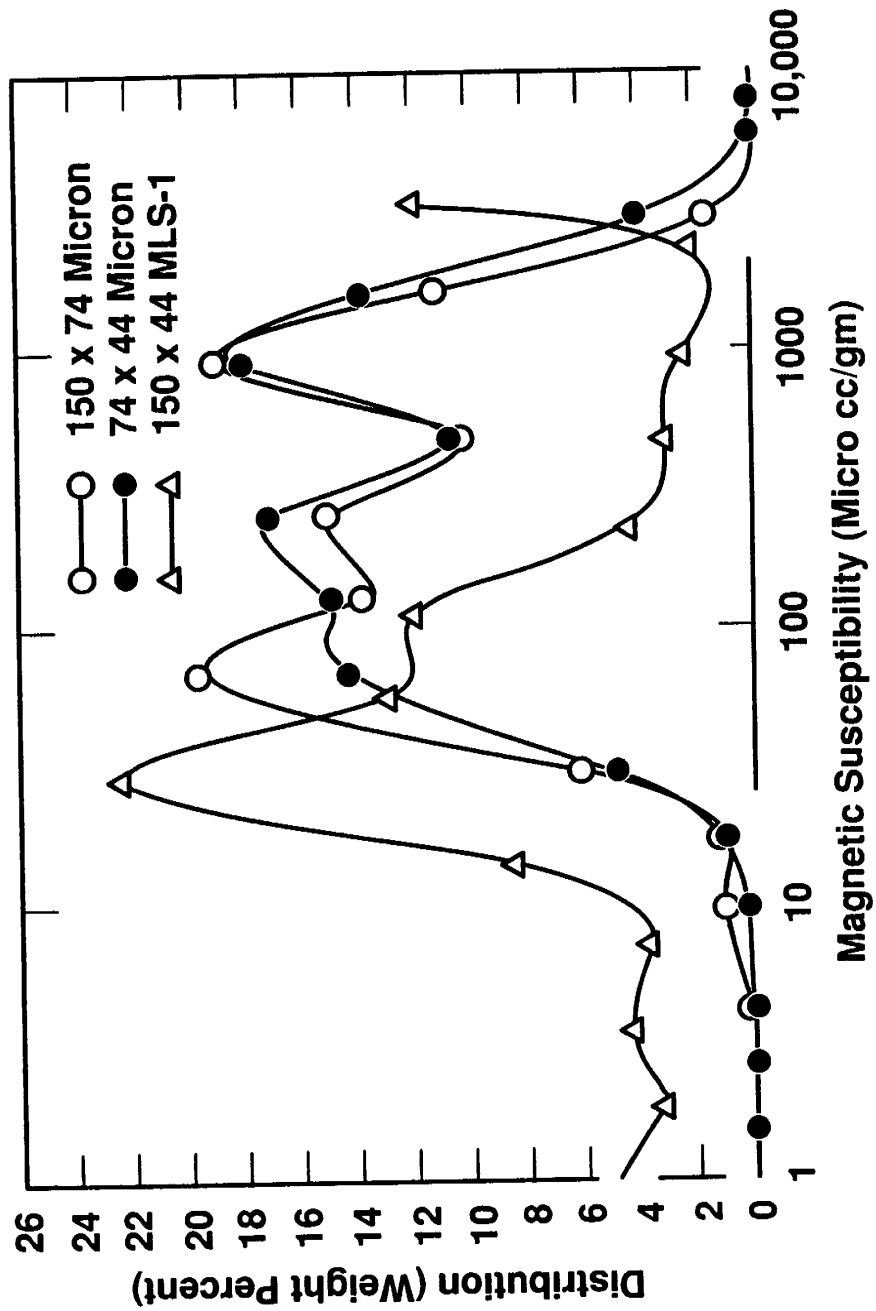
ILMENITE FLOW SHEET LUNAR SOIL 71061



ILMENTE FLOW SHEET
Lunar Soil 71061

Size Range (Microns)		<20	>20	>20	<20
Susceptibility Range (Micro cc/gm)		>93	>41<122	<60	>41<122
Recovery (wt%)	100	19.14	21.3	35.29	24.27
	<u>Feed</u>	<u>Magnetics</u>	<u>Ilmenite</u>	<u>Low Iron Product</u>	<u>Untreated <20 Micron</u>
SiO ₂	40.2	38.8	34.6	43.3	41.7
CaO	10.1	9.2	8.1	11.4	10.6
MgO	10.1	10.3	9.6	11.0	9.2
Na ₂ O	0.4	0.4	0.3	0.4	0.5
K ₂ O	0.1	0.1	0.1	0.1	0.1
FeO	17.9	19.2	23.1	16.1	15.0
TiO ₂	9.8	10.7	15.8	7.0	7.9
Al ₂ O ₃	10.0	9.8	7.0	9.4	13.5
Cr ₂ O ₃	0.5	0.5	0.5	0.4	0.4
MnO	0.2	0.2	0.3	0.2	0.2
NiO	0.0	0.0	0.0	0.0	0.0

Weight Distributions Apollo 11 Soil #10084 and MLS-1



ITBC FORM

Issues to be Considered

Issue:

To fully test the practicality of lunar oxygen production processes, several (not just one) simulants for each process would be desirable. Each process should be tested against a series of feedstocks that cover the range of likely feed properties.

Each simulant should have a fairly narrow range specified on bulk and mineral composition, for example. A narrow range on the simulant properties should be specified to allow multiple batches of a simulant to respond similarly in an experiment. If only one simulant per process was procured, it would likely be a simulant with "average" properties. However, from an engineering point of view it would be better to test a process with simulants that cover the whole range of properties that could likely be fed to a process. This may take as many as three simulants per process—one with properties at one end of the range, one at another, and one average.

Possible Resolution:

Before specifying simulants, a study should be conducted to determine the likely range of properties of a feedstock that would be mined and fed to a process, and the possible effects on the process. (Note that process upsets and product quality/production rate swings are common terrestrial plant response to swings in feed properties.) The objective of the sensitivity study would be to determine if one or more simulants are needed for a particular process.

Name: Eric L. Christiansen

Organization:

NASA JSC/SN3

ITBC FORM

Issues to be Considered

Issue:

Simulant requirements for Magma Electrolysis and Fluxed (Fluoride) Electrolysis now list only "Bulk Chemistry" (7a) as necessary (for oxygen and metals production). However, mineralogy is also likely to be important to these processes. For magma electrolysis, mineralogy influences melt temperature, melt viscosity, and solubilities of products within melt. For fluxed electrolysis mineralogy is even more important because it influences solubilities of the feed materials in the melt as well as the other considerations in magma. Mineralogy influences energy requirements, which is an engineering parameter that must be experimentally determined. To a lesser extent, feed size also influences how well (speed) the feed dissolves in melt for both magma and fluxed electrolysis. Thus, feed size influences cell efficiency/productivity, which translates into cell size.

Possible Resolution:

Add (7b) Mineral Chemistry to requirements for simulants for fluxed and magma electrolysis. Feed size can be specified (1a) but is not as important--simulant should just have same average grain size as lunar feed. So "71,b > 1a" is my recommendation.

Name: Eric Christiansen

Organization:

NASA JSC/SN3

ITBC FORM

Issues to be Considered

Issue:

- (a) Construction is a vital first step for human existence and manufacturing in any habitat, extraterrestrial or terrestrial. Hence, although it is necessary that production of oxygen (on the Moon) is the first step for emphasis, the subject of development of construction materials (from lunar soils) should also remain a significant step of initial concern.
- (b) Engineering and mechanics (material behavior) aspects appear to be inadequately covered. For instance, there is a need for proper and precise definition of required geomechanical properties of simulants and associated testing.

Possible Resolution:

- (a) Include in plans and in research significant emphasis on construction needs including and beyond those for the initial plans for the lunar habitat.
- (b) Utilize fully available basic and applied knowledge, including on material behavior for the design of habitats.
- (c) Increase participation in various committees of civil engineering and mechanical (materials) oriented persons, for geomechanical properties and testing.

Name: Chandra S. Desai

Organization:

Department of Civil Engineering and Engineering Mechanics
University of Arizona
Tucson AZ 85721

ITBC FORM

Issues to be Considered

Issue:

Development of models and dimensionless numbers to estimate and evaluate the validity of stimulant tests and to provide guidance on how to select stimulants and conduct tests. Similarity is based on having a model and dimensionless numbers that indicate how close a simulated experiment is to the real situation considered. This approach is widely used in engineering and is the backbone of engineering experimentation. The issue at stake is whether such an approach can be developed for lunar simulants.

Possible Resolution:

To review and investigate the feasibility of developing models and dimensionless numbers for determining the effectiveness of simulants and for facilitating the selection of the correct simulants. Additional benefit is economic, savings in both time and money.

Name: Willy Sadeh

Organization:

Colorado State University

ITBC FORM

Issues to be Considered

Issue:

Lunar Base Agriculture

In every pioneering endeavor conceived by man, plans for supplying food, clothing, and shelter had to be derived. In a future lunar base, implementation of a bioregenerative controlled ecological life support system (CELSS), in discrete developmental phases, can lead to autonomy of lunar inhabitants and reduce the cost of resupply from Earth. Lunar base agriculture can aid in water recycling/gaseous wastes removal, O₂ generation, and food production.

Possible Resolution:

Utilization of simulants for agricultural research, which approximate the particle sizes, surface area, chemical properties, modal composition, and chemical reactivity of lunar surface materials, will generate answers for CELSS implementation. However, preliminary research needs to be conducted presently to insure proper usage in a CELSS system.

Name: G. W. Easterwood, Ph.D.

Organization:

University of Florida

ITBC FORM

Issues to be Considered

Issue:

Should lunar agriculture be represented on a Moon base to provide food, O₂, water purification, and waste disposal? Apparently, someone at NASA has made the decision that it is more economical to ship food from Earth and use physical/chemical methods for O₂ production, water purification, and removal of CO₂ and wastes. My questions are these:

1. Where are the data that led to this decision?
2. Why does CELSS exist?
3. Why do Bob McElroy and Mel Aurner think that bioregenerative life systems, rather than physical/chemical, will be important on a lunar base?
4. If agriculture is used on a lunar base, should lunar soils be used with or without nutrient solutions?

Possible Resolution:

Get the data to answer these questions and make them available to the *general* scientific community so that scientists such as me and many of my colleagues don't waste our time. If the data are not available, my colleagues and I can help generate them so that NASA can make reasonable, justifiable decisions.

Name: Cleon W. Ross, Plant Physiologist

Organization:

Department of Plant Pathology and Weed Science
Colorado State University

ITBC FORM

Issues to be Considered

Issue:

Simulants for Agriculture

Agriculture in a lunar outpost/base is imperative to insure supply of food toward self-sufficiency and autonomy. One cannot envision people on the Moon and on Mars without the capability to produce some food. In addition, agriculture or plant modules can play a significant role in recycling and treatment of human waste and in producing oxygen for humans.

Possible Resolution:

Development of simulants specifically suited for agriculture development on the Moon.

Name: Willy Sadeh

Organization:

Colorado State University

ITBC FORM

Issues to be Considered

Issue:

Lunar simulant soil for agriculture. The growth of agricultural products on the lunar outpost serves several needed purposes:

1. Survival: Growth of food on the Moon builds in a safety factor for the astronauts. Resupply may be inadvertently delayed by a Challenger-type accident.
2. Cost: The high cost of space transportation works against constant resupply of foodstuffs vs. supplying several pounds of plant seeds that could produce hundreds of pounds of food.
3. Life Support: Incorporating plants into the lunar base O₂ system will increase O₂ supply and provide a passive and possibly low-cost regeneration of waste gases.
4. Human factors: Growing plants will improve the psychological health of the astronauts who will be in a very stark, dull living environment. Note the growth of plants on the Mir for the psychological health of the cosmonauts.
5. Mars Mission: Plants will have to be used on the Mars base and Moon base could be the testbed.

Possible Resolution:

1. Establish a lunar soil simulant for agriculture.
2. Incorporate agriculture production/research in the lunar outpost program.

Name: Chris Shove, Ph.D., Director

Organization:

The Florida Space Research Foundation
200 S. Washington Avenue #2
Titusville FL 32780

ITBC FORM

Issues to be Considered

Issue:

What lessons were learned during the development and usage of lunar simulants during pre-Apollo testing?

Possible Resolution:

Although the pre-Apollo simulants were based only on information sent back from automated landers, a very extensive equipment testing program was conducted. Include in this report a section on the history of lunar simulants. The report *Lunar Simulant Survey Report* by Nels Forsman contains a brief history of simulated rocks and soils used in pre-Apollo testing and an annotated bibliography, and may be an excellent starting point.

Name: Judy Allton

Organization:

Lockheed Engineering & Sciences Company

ITBC FORM

Issues to be Considered

Issue:

In what ways can the NASA organization, charged with coordinating lunar simulant activities, encourage interest in the lunar outpost among science and engineering students?

Possible Resolution:

The organization can include educational users as well as research users in providing services. For example, the Simulant Archivist could announce, through educational channels, the commercial availability of simulants and provide special brochures explaining how to acquire and use lunar simulants. Archiving of student simulants would not be required. NASA may even desire to purchase simulant for distribution to students. In this case, distribution to educators could be handled through existing programs for teachers. The simulant organization would recommend or approve the simulant, prepare the descriptions, and be available to answer questions.

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